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Kirti N. Ghia and Urmila Ghia

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A three-and-a-half year multi-tasked research project was pursued by the present investigators to study two- and three-dimensional low-speed viscous separated flow problems under AFOSR sponsorship between October 1986 and April 1990. The major objectives of this study were to understand the effect of flow separation, unsteadiness, three-dimensionality and nonlinear dynamics in simple two- and three-dimensional flows and, subsequently, examine the control of these flows. In the process of achieving these objectives, significant effort was directed toward developing basic computational methods which were made available to interested researchers and organizations involved in computational fluid dynamics (CFD) research. The several analyses developed include two-dimensional Navier-Stokes (NS) analyses for steady and unsteady bluff-body separation and massively separated flow past generalized airfoils at high angle of attack; a passive flow-control analysis using a flap for a generalized airfoil; active

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flow control analyses using an oscillating flap modulated suction/injection and free-stream unsteadiness; nonlinear dynamical systems analysis for low-speed separated flows; and, finally, three-dimensional analysis using velocity and vorticity for internal flows. The finite-Re results obtained for steady bluff-body separation revealed some anomalies in the existing theoretical models and should help in improving these models. The Navier-Stokes analysis for unsteady separation past a circular cylinder provided very accurate prediction of Reynolds stresses from first principles. The generalized airfoil analysis provided an analytical grid-generation technique using Schwarz-Christoffel conformal mapping. To the authors' best knowledge, this led, for the first time, to a direct treatment of the Kutta condition, and analytic closed-form potential flow solutions for arbitrary bodies. The details of the trailing edge geometry showed significant changes in lift for the overall flow field. Results of the active flow control analysis using the oscillating flap showed a significant reduction in the reattachment length of the primary separation bubble and, hence, suggest the use of the flap as a viable control mechanism. As an additional benefit, the analysis provides a means for studying flow past deforming bodies and also fluid-structure interaction phenomena. Numerical experiments using other control strategies including modulated suction/injection and free-stream unsteadiness were also conducted, but these need further study in order to lead to conclusive results. Further, toward designing a formal algorithm for flow control application, the results were examined in the phase space. Hence, the results for circular and elliptic cylinders as well as Joukowski airfoils at high angle of attack were examined using tools from dynamical systems theory. The results for the flow past a circular cylinder led to the correct interpretation of the comprehensive data of Professor Sreenivasan. To the authors' best knowledge again, windows of chaos were observed, for the first time, for flow past a 12% symmetric Joukowski airfoil using the unsteady NS analysis. The results showed period doubling, flow bifurcations and the universal route to chaos through quasi-periodicity, a Ruelle-Takens-Newhouse scenario. The three-dimensional unsteady NS analysis developed is very accurate and extremely efficient, but is limited to coarse grids due to its large memory requirement. The various analyses developed have provided further insight into important fluid mechanics phenomena and their control; additional work is needed in some cases to bring these studies to their final conclusion.

ABSTRACT

A three-and-a-half year multi-tasked research project was pursued by the present investigators to study two- and three-dimensional low-speed viscous separated flow problems under AFOSR sponsorship between October 1986 and April 1990. The major objectives of this study were to understand the effect of flow separation, unsteadiness, three-dimensionality and nonlinear dynamics in simple two- and three-dimensional flows and, subsequently, examine the control of these flows. In the process of achieving these objectives, significant effort was directed toward developing basic computational methods which were made available to interested researchers and organizations involved in computational fluid dynamics (CFD) research. The several analyses developed include two-dimensional Navier-Stokes (NS) analyses for steady and unsteady bluff-body separation and massively separated flow past generalized airfoils at high angle of attack; a passive flow-control analysis using a flap for a generalized airfoil; active flow control analyses using an oscillating flap modulated suction/injection and free-stream unsteadiness; nonlinear dynamical systems analysis for low-speed separated flows; and, finally, three-dimensional analysis using velocity and vorticity for internal flows. The finite-Re results obtained for steady bluff-body separation revealed some anomalies in the existing theoretical models and should help in improving these models. The Navier-Stokes analysis for unsteady separation past a circular cylinder provided very accurate prediction of Reynolds stresses from first principles. The generalized airfoil analysis provided an analytical grid-generation technique using Schwarz-Christoffel conformal mapping. To the authors' best knowledge, this led, for the first time, to a direct treatment of the Kutta condition, and analytic closed-form potential flow solutions for arbitrary

bodies. The details of the trailing edge geometry showed significant changes in lift for the overall flow field. Results of the active flow control analysis using the oscillating flap showed a significant reduction in the reattachment length of the primary separation bubble and, hence, suggest the use of the flap as a viable control mechanism. As an additional benefit, the analysis provides a means for studying flow past deforming bodies and also fluid-structure interaction phenomena. Numerical experiments using other control strategies including modulated suction/injection and free-stream unsteadiness were also conducted, but these need further study in order to lead to conclusive results. Further, toward designing a formal algorithm for flow control application, the results were examined in the phase space. Hence, the results for circular and elliptic cylinders as well as Joukowski airfoils at high angle of attack were examined using tools from dynamical systems theory. The results for the flow past a circular cylinder led to the correct interpretation of the comprehensive data of Professor Sreenivasan. To the authors' best knowledge again, windows of chaos were observed, for the first time, for flow past a 12% symmetric Joukowski airfoil using the unsteady NS analysis. The results showed period doubling, flow bifurcations and the universal route to chaos through quasi-periodicity, a Ruelle-Takens-Newhouse scenario. The three-dimensional unsteady NS analysis developed is very accurate and extremely efficient, but is limited to coarse grids due to its large memory requirement. The various analyses developed have provided further insight into important fluid mechanics phenomena and their control; additional work is needed in some cases to bring these studies to their final conclusion.

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SECTION 1

OBJECTIVES

An analytical-numerical study was pursued by the present investigators under AFOSR sponsorship during October 1986-October 1989. The primary objectives were: (i) To gain better understanding of 2-D unsteady separated flow and, subsequently, its control; (ii) To provide a direct implicit technique to study 3-D internal flows. Some secondary objectives were also formulated; these were: (i) To analyze the flow instabilities observed in "direct numerical simulation" (DNS) using fully implicit methods; (ii) To develop an anisotropic turbulence model to analyze high-Reynolds number (Re) flows including turbulence-driven secondary flows. It should be noted that the authors are continuing to develop DNS methodology for 2-D and 3-D unsteady flows without use of any turbulence models. In the literature, the term DNS techniques is used primarily with reference to simulating 3-D unsteady flows.

The major research thrust was directed in developing several major computational fluid dynamics analyses for studying unsteady separated flow and its control. For 2-D flows, unsteady massive separation was studied using bluff bodies as well as airfoils at high angle of attack in the deep post-stall regime. The flow control analysis was developed for flows with temporally deforming boundaries, thus making the analysis useful for studying other aspects of unsteady separated flows, namely, fluid-structure interactions. In general, DNS methodologies are limited to low-Re flows; hence, to facilitate the analysis of complex high-Re viscous flows, a nonlinear two-equation turbulence model was also investigated.

The significant accomplishments made toward achieving the various objectives just stated are briefly described next.

SECTION 2

DESCRIPTION OF SIGNIFICANT ACCOMPLISHMENTS

All of the areas of research initiated and the progress, as well as specific achievements, made in these studies during the three-year grant period are briefly summarized in the following subsections.

2.1 2-D Flow Separation

A few simple 2-D geometries were studied to shed light on the unsteady separation phenomenon. In addition, a small amount of steady separated flow work was also pursued, so as to aid further development of the asymptotic theory for steady separation and to bring to completion an effort initiated under the preceding AFOSR Grant. This work was carried out for the symmetric flow past a circular cylinder and is discussed first, and is followed by a description of the unsteady separated flow work.

2.1.1 Symmetric Circular Cylinder

Self-induced oscillatory motions in the near wake of a symmetric Joukowski airfoil at angle of attack, leading to a buffeting stall phenomenon, was successfully analyzed by K. Ghia, Osswald and U. Ghia (1986). Their study used unsteady Navier-Stokes (NS) analyses developed under a grant from NASA. The numerical method developed was a fully-implicit technique which had experienced no difficulties in their study for $10^3 \leq Re \leq 10^4$. This accurate and robust method provided the impetus to study separated flow past a circular cylinder, with symmetry being assumed for the flow. Earlier investigators who had attempted to study this flow had experienced considerable difficulty, as was indicated by Fornberg (1980), in accurately capturing the diverse length scales and, thereby, contributing toward an accurate description of the large-Re flow structure.

K. Ghia, U. Ghia, Osswald and Liu (1987) had analyzed this flow past a circular cylinder and provided detailed results at finite-Reynolds (Re) number. The unique feature of this analysis was that steady flow results were obtained as time asymptotic solutions of the unsteady NS equations.

The results of their simulation were in agreement with the numerical results of Fornberg (1985) obtained using the steady form of the NS equations. However, they did not completely conform to the new laminar-flow structure for high Re based on a massive eddy of O(Re) proposed by Smith (1985). In particular, the results did not show O(1) thickness for both the shear layer past the center of the main eddy and the return jet. This can be observed from the velocity vectors depicted in Fig. 1 for flow configurations with Re = 100 and 500; also observed here is the constant vorticity present in this eddy. Besides obtaining the structure of flow separation at finite Re, the analysis raised several new questions, which can only be answered through further analysis. The numerical method did suffer from slow rate of convergence. Hence, a Newton's method was developed by Rice, K. Ghia, Osswald and U. Ghia (1988). This new method, however, did not significantly improve the convergence rate of the previous analysis of the authors. In his closing remarks in the book on boundary-layer separation, Sir James Lighthill (1987) has stated that "Professor K. Ghia showed that computation based on the Navier-Stokes equations for unsteady motion is also extremely powerful in the vorticity equation form."

2.1.2 Circular Cylinder

The separated flow past a circular cylinder without the assumption of flow symmetry was investigated using the 2-D unsteady NS analysis developed by the PIs and their associates. For flow impulsively started from rest, Fig. 2 shows the comparison of their results for the velocity along the wake

centerline and wake boundaries for Re = 200 and 550 at early times with the results of Bouard and Coutanceau (1980); the agreement in the results is very good. To thoroughly check the prediction capabilities for large time, the normal Reynolds stress $(\overline{u'u'})^{1/2}$ was obtained and compared with the experimental results of Nishioka and Sato (1978) in Fig. 3. The present results shown in Fig. 3(a-c) are in excellent agreement with the experimental data shown in Fig. 3d. The flow structure is depicted in Fig. 4 where, for Re = 200, the stream function and vorticity contours are presented for one cycle. These detailed and accurate NS results at finite Re are extremely useful in developing the theory for unsteady separation. Details of this analysis have been presented by K. Ghia, Liu, U. Ghia and Osswald (1987). Additional results for this flow configuration will be discussed in Section 2.3 on chaotic flow.

2.1.3 Airfoil at High-Angle of Attack

In their earlier research, the present investigators had extensively studied the flow past two-dimensional airfoils. Their studies on stationary airfoils were motivated primarily by the need to understand the flow in the near- and post-stall regimes so that strategies would be devised for increased lift. The unsteady NS analysis used conformal mapping, along with DNS methodology. The use of an analytical mapping technique to generate the grid prevented numerical errors from entering the calculations and contaminating the flow solutions. Also, the analysis provided the method of analytical continuation to treat the metric discontinuity at the branch cut, permitting an asymmetric C-grid shown in Fig. 5, for which the region of high resolution more closely followed the wake centerline.

The DNS methodology was refined to study flows for $10^4 \leq Re \leq 10^5$. The airfoil chord was used as the characteristic length in the definition of Re. A finer grid with (441, 61) points was used in computing the flows for $10^4 \leq Re \leq 10^5$. For the case with $Re = 10^4$, the instantaneous stream function and vorticity contours are given in Figs. 6a and 6c, with the velocity vectors being depicted in Fig. 6e. The flow separates and a separation bubble extends over 42% of the chord near the trailing edge (TE). The additional results obtained by K. Ghia, Osswald and U. Ghia (1989) lead to the conclusion that, at fixed angle of attack, increase in Re increases the extent of the bubble. The intense interactions between the vortices from the leading and trailing edges are vividly seen in Fig. 6c. The corresponding time-averaged contours of ψ and ω are depicted in Figs. 6b and 6d, whereas the velocity vectors are shown in Fig. 6f.

This analysis was further extended by Osswald, K. Ghia and U. Ghia (1989) to consider airfoils of arbitrary cross-section. It extended the Schwarz-Christoffel conformal mapping technique of Davis (1983) to provide grids for NACA airfoils. To the PIs' best knowledge, the work of Osswald, K. Ghia and U. Ghia (1989) provided, for the first time, a direct treatment of the Kutta condition and analytic, closed-form potential-flow solutions for arbitrary bodies. The various configurations investigated by them are shown in Table 1. The NACA 0012 airfoil has been used in validation studies by many researchers, but none have examined the influence of the TE geometry. The present authors believe that this critical point may exert significant influence in high-Re flows. The results presented here show this effect to some degree, even for low-Re flows. The bluff TE shown in Fig. 7a obtained from the original NACA 4-digit thickness distribution, is modified to give either a rounded TE or a wedge TE. Details of this

modifications are given by Osswald et al. (1989). In Fig. 7(c-d) for angle of incidence $\alpha = 5°$, the separation processes are very different and, as such, higher $C_L = 0.55$, shown in Fig. 7f, is obtained for the wedge TE. Typical flow results are shown in Figs. 7(g-j) at t=35, and display significant differences as a consequence of the TE geometries.

2.2 Unsteady Flow and Its Control

Active control/management of separated flows was studied by considering internal as well as external flow configurations. For internal flow, a mechanical flap was used to alter the vorticity content of the separated flow configurations. For the external flow, some attempts were made using two different approaches. A thick-plate geometry was chosen for which modulated suction/injection experiments were attempted but the work was not carried sufficiently forward due to lack of time. Also, an unsteady free stream was considered as a possible control mechanism to be used with flow past an elliptic cylinder. Finally, numerical experiments were also conducted using a passive control, namely a flap on the suction surface. The status of all these studies is reported here.

This aspect of the research consisted of two phases (i) Accurate simulation of unsteady separated flows via direct solution of Navier-Stokes equations, and (2) Control of these flows by the mechanical device of an oscillating flap. A channel with a backward-facing step, termed the backstep channel, was used as the model problem (Fig. 8). This geometrically simple configuration exhibits a flow extremely rich in physical features, including separating and reattaching shear layers interacting with other viscous effects, and leading to a very complex flow structure. For asymptotically large Reynolds number, the subscale flow structure embedded under a boundary-layer-like region may be analyzed by the

multi-structured asymptotic analyses of Sychev (1972), Stewartson (1974), Messiter (1975) and Smith (1977, 1979). However, for complex internal flows at finite Reynolds number, the prevailing flow may differ significantly from the predictions of the asymptotic theory. Therefore, the present approach consisted of formulating the problem using the complete Navier-Stokes equations, with guidance being taken from the asymptotic theory to derive the appropriate scaling and, hence, the grid-point clustering needed for the various critical regions of the flow.

2.2.1 Basic Backstep Channel Flow

The doubly-infinite backstep channel flow problem was formulated using the strong-conservation-law form of the unsteady incompressible Navier-Stokes equations in terms of vorticity and stream function, in generalized orthogonal curvilinear coordinates. These coordinates were generated as clustered conformal coordinates. The conformal transformation mapped the backstep channel in the physical plane to a straight channel in the conformal plane. One-dimensional clustering functions, dependent on the Reynolds number and the asymptotic behavior of the flows, provided suitable grid-point distribution in the separation and reattachment regions, in the boundary layers as well as the inflow and outflow regions, while also mapping the doubly-infinite straight channel in the conformal plane to a unit square in the computational plane. The numerical method developed consisted of solving the vorticity-transport equation using the alternating direction implicit (ADI) method, while the stream-function equation was solved by direct block Gaussian elimination (BGE). The details of the transformations and the numerical solution procedure have been described by K. Ghia, Osswald and U. Ghia (1989). The asymptotic behavior of the finite-differenced equations near infinity is examined and the numerical method is

carefully developed so as to lead to second-order accurate solutions with minimal dispersive error.

A comparison of the results of the present numerical analysis with the laser-Doppler experimental data of Armaly and Durst (1980) is shown in Fig. 9. Here, h_s is the height of the step, Re_s is the Reynolds number based on h_s, and L_1 is the length of the primary eddy, i.e., the reattachment length of the primary separation bubble off the backstep. As seen here, the present 2-D results are in excellent agreement with the experimental data of Armaly and Durst (1980), provided that only the primary separation bubble exists in the flow field. Thus, the agreement is excellent for $Re_s \leq 212$. For $Re_s > 212$, the present 2-D results depart from the experimental observations of Armaly and Durst (1980). This departure is to be expected since Armaly et al. (1983) have found evidence of three-dimensionality in their earlier data reported by Armaly and Durst (1980) for $Re_s \gtrsim 212$. In fact, they found that the onset of three-dimensionality coincided with the first occurrence of the secondary separation bubble (on the upper wall). A possible mechanism for this abrupt change in flow structure has been presented by K. Ghia, Osswald and U. Ghia (1989).

Steady-state as well as transient flow results have been obtained for a number of configurations encompassing the laminar range. For configurations with only one separation bubble at the lower wall, a similarity was shown to exist with respect to the channel geometry. The reattachment length L_1/h_s of the primary separation bubble on the lower wall, for various geometries, collapses into a single curve when plotted as a function of Re_s. This similarity is lost when an additional separation bubble forms on the upper

wall; this also marks the onset of three-dimensionality in the flow. To the best knowledge of the authors, similar results have not been previously reported in the literature. By a detailed examination of the case with $h_s = 0.48515$ and $Re_s = 695$, the effect of three-dimensionality has been quantified by Osswald, K. Ghia and U. Ghia (1989), as is the streamwise extent of the range of upstream and downstream influence due to the step.

For the same value of h_s, i.e., $h_s = 0.48515$, the case with $Re_s = 1885$ does not attain a steady state; rather, it exhibits a persistently unsteady limit-cycle behavior consisting of alternating vortex shedding along both the upper and lower channel walls. Based on outlet channel width L_{out} and outlet velocity U_{out}, the corresponding values of the Reynolds number Re is 2000. Figure 10 shows a typical shedding cycle associated with the primary recirculation zone. The Strouhal number S of the shedding motion is evaluated to be $S = 0.38$ where $S = f\, L_{out}/U_{out}$, with f being the shedding frequency. The well-developed large eddies, with length scales of $O(h_s)$, are shed periodically, and alternately, from the reattachment point of the primary bubble at the lower wall and the fluctuating secondary separation bubble at the upper wall. Consequently, a 'vortex street' is formed in the channel downstream of the primary reattachment zone. The wavelength, or the distance between the centers of the successive eddies, is approximately $1.9\ L_R$. The eddies are convected with the flow, their strength diminishing with distance downstream, until they are dissipated entirely by approximately 15 channel heights downstream.

Due to vortex shedding, the flow in the zone downstream of the primary reattachment point is very unsteady. Also, the length of the primary

separation bubble fluctuates, with the impinging shear layer first moving downstream and then "leaping" abruptly back upstream as a discrete eddy sheds off.

The time-averaged stream function and vorticity contours are presented in Fig. 11. The time averaging has been performed over a period of approximately 22 characteristic times. The three separation bubbles persist in the time-averaged flow, as seen in Fig. 11(a). Thus, the present unsteady Navier-Stokes analysis is capable of computing many of the features characteristic of turbulent flows as described by Eaton and Johnston (1981). The complete knowledge of the instantaneous motion as well as the mean motion can make it possible to determine statistical information about the flow.

Additonal characteristics of this unsteady flow with multiple separation bubbles are described by K. Ghia, Osswald and U. Ghia (1989).

2.2.2 <u>Control of Separated Flows Using Oscillating Flap</u>

The backstep channel configuration discussed in the preceding section was used as a candidate flow for formulating a flow control mechanism and for developing the necessary theoretical and numerical analyses and algorithms. The case with Re = 2000 had exhibited persistent unsteadiness and was, therefore, used for this purpose.

Control was implemented by simulating a flap mounted within the primary separation bubble on the lower wall, downstream of the step, and driving the flap to oscillate in some prescribed manner so as to alter the vorticity content of the primary separation bubble. The geometry of the flap, its location with respect to the backstep and the waveform of its motion comprise the parameters of this flow control problem. The first major task in this phase of the work consisted of determining a coordinate

transformation that would generate a boundary-aligned coordinate system for arbitrary orientations of the flap. In addition, it was necessary to have a capability for considering curved boundaries so as to admit a flap with a rounded tip. The required time-dependent boundary-oriented clustered conformal coordinates were generated using a generalized Schwarz-Christoffel mapping [Davis (1983)], followed by suitable 1-D contraction mappings to resolve the critical regions of the flow. Details of the method for developing the transformation and determining the coordinates for arbitrary orientations of the general oscillating flap have been given by Zuo, U. Ghia and K. Ghia (1988). The approach guarantees the orthogonality of the resulting coordinates. It also permits the high efficiency of the BGE procedure to be retained by guaranteeing time-invariance of the differential operator for the stream-function equation, even in the presence of temporally deforming grids.

The governing equation for vorticity transport in this flow configuration with the oscillating flap contains grid-speed terms which are evaluated using the mapping at two successive levels of time. The boundary conditions required special care for points on the moving flap, where both tangential as well as normal components of the velocity are non-zero, even though the flap is non-porous. The details have been described by U. Ghia, Zuo and K. Ghia (1989). Figure 12 shows the instantaneous stream-function contours for the backstep channel, of unit height, with a flap of height 0.25, located at $x=1$, and oscillating sinusoidally at reduced frequency $F=0.16$, based on channel height. This frequency corresponds to a reduced frequency of 0.04, based on flap height. The Reynolds number Re, based on channel height, is 2000. Comparison of these results with those obtained previously (Fig. 12) for the backstep channel without the flap shows that,

for example, at Time ≈ 60, the control flap leads to approximately 15 percent reduction in the reattachment length of the primary separation region.

Associated with the control flap are various parameters such as its location and geometry as well as the waveform and frequency of its motion. Of these, the frequency is considered to be the more significant one. Figure 13 shows the results obtained for the case with F=0.25, i.e., a reduced frequency of 0.0625 based on flap height. The length of the primary separation zone is generally smaller than that for the case with F=0.16 in Fig. 12, and shows a reduction of nearly 25 percent as compared to the basic backstep flow without the flap (Fig. 10).

In order to characterize the formation and shedding of the starting vortex and the separation that follows, another configuration was also considered, namely, that of a flap that rises up to a designated angle into a boundary layer and then remains stationary until the flow stabilizes. This configuration was intended to better represent the flat-plate configuration used in the corresponding experiments of Koga et al. (1988) and Acharya (1989).

It is necessary to mention, however, that the experiments of Koga et al. (1988) are for $Re_f \approx 500{,}000$. The present computational results have been obtained using direct simulation of the unsteady Navier-Stokes equations, i.e., with no turbulence modeling. As many as (598x51) grid points have been employed in these computations. Even with such refined grids, with the best clustering possible, the direct solutions have been limited to $Re_f \approx 4{,}000$. On the other hand, the lowest value of Re_f at which reliable experimental measurements may be possible has been estimated as 10,000 by Acharya (1989). Hence, the numerical analysis and computer code have also

been generalized to accommodate a Baldwin-Lomax (1978) turbulence model, so that higher values of Re_f may be considered in the computations. Further numerical experiments need to be conducted with this analysis using more general turbulence models.

The results described in the last two subsections serve to demonstrate that a capability has been developed for numerically simulating 2-D flows in temporally deforming geometries. The analysis has been demonstrated via results obtained for flows with an oscillating flap as an active flow-control mechanism.

2.2.3 Control of Separated Flows Using Modulated Suction/Injection

The flow along a semi-infinite plate with finite thickness and sharp shoulder was investigated using the unsteady NS analysis of U. Ghia and Davis (1974). The Navier-Stokes equations were written in terms of similarity-type vorticity and stream function variables. U. Ghia and Davis (1974) had investigated the steady flow past the thick plate configuration; the unsteady flow was investigated by Ramamurti, U. Ghia and K. Ghia (1989). A clustered conformal C-grid was used in the study, with the clustering transformations being 1-D analytical mappings. The stream function equation was solved using a multigrid-strongly implicit (MG-SI) procedure, whereas the vorticity-transport equation was solved using a factored ADI scheme. The basic flow was successfully simulated and the detailed results have been given by Ramamurti et al. (1989). Control strategies using modulated suction/injection were planned, but lack of time did not permit generation of meaningful results for this configuration. This control strategy could have led to the understanding of the entrainment process near the sharp shoulder as well as Kelvin-Helmholtz instability of the free shear layer and the shedding type instability of the entire bubble.

2.2.4 Unsteady Free Stream - A Control Mechanism

To investigate the effect of unsteadiness in the free stream, the flow past an elliptic cylinder was investigated. This geometry was chosen with the understanding that an experimental study for a 4:1 ellipse was to have been initiated by Professor Ho at the University of Southern California. The basic uniform flow past this 25% thick elliptic cylinder was simulated by Blodgett, K. Ghia, Osswald and U. Ghia (1988) by developing an unsteady NS analysis. The basic flow also examined the effect of blunt TE on flow separation. To accurately evaluate this effect, Blodgett et al. (1988) used a grid of (380, 46) with 140 points around the ellipse. This permits reasonable resolution of the region of high vorticity in the shear layer that emanates near the leading stagnation point (LSP). Figures 14(a-c) show instantaneous contours of pressure, stream function and vorticity at t=110. The vorticity contours clearly show that the gradients due to vorticity production near the LSP for this bluff body configuration are properly resolved. This flow also permits study of vortex interactions. The power spectrum of C_L exhibits the presence of a subharmonic frequency, suggesting that a period doubling has occurred. Since Professor Ho altered his plans and the data that was needed was never generated, plans had to be changed at this end also and this investigation was therefore not pursued further. As a means of studying control strategy, the vorticity flux on the surface of the elliptic cylinder was altered and its effect on the separation process was assessed. This numerical experiment was motivated by the fact that a change in the vorticity flux implied a change in the local pressure gradient - a quantity closely related with the mechanism of flow separation. In addition, attempt was also made to look at the effect of unsteady free stream using the data of Mathioulakis and Telionis (1989) for Re = 14,300

and $\alpha = 14°$. Although the basic flow data was generated, the control experiments could not be completed because of insufficient information available from the paper.

2.2.5 Passive Control: Effect of Control Flap on Suction Surface of Airfoil

The purpose of this research was to achieve and analyze numerical solutions and aerodynamic properties of the NACA0012 airfoil with and without a control flap, at different angles of attack. A numerical grid generation based on conformal mapping was employed to develop an orthogonal surface-oriented coordinate system for the complex geometry of the airfoil with general orientation of the control flap, as shown in Fig. 15. For this study, the Navier-Stokes equations were solved using the ARC2D code developed by the NASA Ames Research Center, so as to also assess the effect of using a compressible-flow thin-layer formulation in primitive variables. The code solves the thin-layer Navier-Stokes equations by an implicit finite-difference scheme using time linearization, approximate factorization and diagonalization of the coefficient matrix.

The numerical results obtained for the NACA0012 airfoil show that steady-state solutions can be achieved for angles of attack between 0° and 12°. When the angle of attack exceeds 12°, the flow remains persistently unsteady. The present numerical results were compared with the available experimental data, and the agreement is quite good. The numerical results obtained for the unsteady C_ℓ, C_d and C_p for the airfoil with a control flap show the feasibility of achieving higher lift coefficients at the higher angles of attack by installing a flap on the upper surface of the airfoil. The unsteady solutions are characterized by a periodic behavior, resulting from the repeated formation and shedding of vortical structures in the flow.

Figures 16 and 17 show the pressure distribution for the case with $\alpha = 12°$, with and without the control flap.

Examination of the unsteady lift coefficient for the NACA0012 airfoil at high angle of attack, i.e., in the range from 16° to 20°, shows that the inclusion of the control flap serves to make the unsteady lift coefficients more regular and with less of a fluctuating pattern, and can provide better and more manageable control of aircraft at high angle of attack. In general, the chordwise location of the control flap has a significant effect on the flow characteristics. The time-averaged drag coefficient decreases as the location of the flap is moved toward the trailing edge. The time-averaged lift coefficient and time-averaged drag coefficient also increase with the increase of angle of attack from 0° to 24°.

The study shows the feasibility of application of numerical predictions in the innovative design of airfoils with control flaps. Further research should examine the effect of flap length and flap orientation angle, and its location on the upper surface.

2.3 Unsteady Flows with Period Doubling, Bifurcations and Chaos

Circular and Elliptic Cylinder

Flow past a circular cylinder was studied by K. Ghia, Liu, U. Ghia and Osswald (1987) and some results depicting the structure of separated flow were discussed earlier in Sec. 2.1.2. Here, the results of an experiment to predict the windows of chaos are discussed. In the near wake of the cylinder, for $Re \leq 200$, Sreenivasan (1985) had observed experimentally that the flow state alternated between that of order and chaos. His comprehensive measurements of this flow for $36 \leq Re \leq 200$ showed quasiperiodicity with multiple frequencies and windows of chaos. In the proximity of $80 \leq Re \leq 90$, he showed a definite window of chaos. Numerical

experiments were conducted and results in the form of lift and drag histories for Re = 80 are shown in Fig. 18 up to characteristic time t = 155. Since the coefficients of lift and drag are global parameters, they are expected to give a more accurate picture of the overall flow field. The power spectral density (not shown here) was obtained for C_L and C_D; it showed that the flow contains only a fundamental frequency and its superharmonics, implying the asymptotic solution to have a limit-cycle solution with a single period. Hence, it was decided to use a procedure similar to that used by Sreenivasan (1985) in his experiment. Thus, K. Ghia et al. (1987) used the time histories of the signals of vorticity at two different locations and obtained the corresponding power spectral density functions, which are shown in Fig. 19. This power spectrum clearly shows the presence of a fundamental frequency and its superharmonics. Also, the results for phase-space portraits and Poincare sections, not shown here, only show a 1-D attractor geometry. On the other hand, for the flow past a 25% thick elliptic cylinder, Blodgett, K. Ghia, Osswald and U. Ghia (1988) were able to see flow bifurcation for Re = 1000, $\alpha = 30°$. Their results in Fig. 14 show the C_L history and the corresponding phase space portrait and Poincare section for this flow. Both the phase space portrait as well as power spectral density show period doubling.

Low-Re unsteady separated flow past a 12% thick symmetric Joukowski airfoil was carefully studied by K. Ghia, Osswald and U. Ghia (1989) to predict the chaotic behavior of this flow. Their systematic study of this flow, using angle of attack as the bifurcation parameter, revealed the presence of hydrodynamic chaos (weak turbulence) at $\alpha = 25°$. Figure 20 shows the results of their study. The instantaneous as well as time-

averaged contours of stream function and vorticity are given in Figs. 20(a-d). The original figures obtained by them were color-shaded with the help of an IRIS 4D-70 GT workstation. The color contours permit the tracking of clockwise and counterclockwise spinning eddies, while providing further insight into the separation process. The attractor geometry shown in Fig. 20(i) was constructed using the independent global observables C_L, C_D and C_M. Their attractor geometry is bifurcated and indeed represents a strange attractor. This fact was also evident in the power spectrum of C_L, which definitely is broad-band, and with the presence of multiple frequencies. They suggested that the universal route to chaos was through quasi-periodicity with more than one incommensurate frequency.

2.4 Analysis of 3-D Flows Using Direct Numerical Simulation Methodologies

As stated earlier, Direct Numerical Simulation (DNS) consists of solving the time-dependent three-dimensional (3-D) Navier-Stokes (NS) equations, which describe the evolution of the flow under consideration, while resolving all of the significant scales of motion without resorting to any turbulence model. Osswald, K. Ghia and U. Ghia (1987) were successful in developing a 3-D unsteady NS analysis with the unique feature that it was developed in terms of velocity and vorticity ($\bar{V}$, $\bar{\omega}$), using generalized orthogonal curvilinear coordinates. The computationally-intensive 3-D divergence-curl vector-differential problem was formulated as a nonsingular (as opposed to over-determined), matrix-vector problem. Another unique feature of the present DNS methodology is that the velocity problem was solved very efficiently by direct inversion using the block-Gaussian-elimination (BGE) scheme. The 3-D vorticity transport equation was solved

using a modification of the Douglas-Gunn alternating-direction implicit (ADI) method which requires the inversion of only scalar tridiagonal matrices, rather than the usual block-tridiagonal system. The rationale for selecting the ($\vec{V}$, $\vec{\omega}$) formulation, as opposed to the primitive-variable ($\vec{V}$, p) formulation or the several possible vector-potential-vorticity ($\vec{A}$, $\vec{\omega}$) formulations, was given by Osswald, K. Ghia and U. Ghia (1987).

Further analysis of the ($\vec{V}$, $\vec{\omega}$) formulation led to the natural separation of the spin dynamics of a fluid particle (the vorticity-transport analysis) from its translational kinematics (the elliptic velocity problem). This natural decoupling facilitated simple and direct application of the boundary conditions, including their implicit treatment in the DNS method, as well as avoided iteration for the nonlinear vorticity-convection terms and led to uniformly second-order accurate results. In their analysis, the governing equations are discretized using central differences for all of the derivatives. The discretization is carried out in a manner that maintains complete consistency, i.e., integral vorticity and velocity constraints, solenoidal velocity condition, etc., are shown to be algebraically guaranteeed, irrespective of grid size and time-step discretization, throughout the entire flow evolution. A consistently-formulated numerical method with a central-difference scheme for all derivatives is also free from aliasing errors. Without these assurances, the simulation results would be highly questionable. The method not only conserves vorticity $\vec{\omega}$, but perhaps also its first moment, although no formal attempt is made to verify conservation of the latter. The technique focuses directly upon the vortex dynamics, and solves the unsteady vorticity-transport equation, together with the divergence-curl probelm for velocity. While six unknowns

($\omega_1,\omega_2,\omega_3,v_1,v_2,v_3$) are implicitly solved for, the computational effort required is equivalent to that of determining only four implicit unknowns, as one unknown is eliminated from the vorticity transport solution prior to coding, and the effect of a second unknown is eliminated from the divergence-curl operator. Indeed, the solution of the vorticity-transport equation is achieved using only six (rather than nine) scalar (rather than block) ADI sweeps, making the direct simulation of the vorticity dynamics extremely efficient. In its present form, the method is uniformly second-order accurate, both spatially and temporally.

The details of the corresponding vorticity transport algorithm were given by K. Ghia, Osswald and U. Ghia (1988), and results for flow inside a shear-driven cube using this methodology were given by Osswald, K. Ghia and U. Ghia (1989).

In engineering, one often talks of two-dimensional turbulent flows and, indeed, such flows are computed routinely. The present research team has taken the liberty of referring to their numerical solutions of the two-dimensional unsteady NS equations as DNS results. For two-dimensional flow, the unsteady analysis uses vorticity and stream function (ω, ψ) as dependent variables in generalized curvilinear coordinates. The corresponding computer code has been well tested for both internal and external flows. Attempts were made to represent the convective terms using fourth-order accurate differencing, thereby improving the overall accuracy of the solutions; however, this approach did not aid significantly in resolving the high-Re flows. In addition to this, an unsteady NS analysis was also developed using velocity and vorticity ($\bar{V},\omega$) as the dependent variables for two-dimensional flows. The details of this analysis were given by Osswald,

K. Ghia and U. Ghia (1988). This approach improves the temporal accuracy of the results from first order to second order.

SECTION 3

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SECTION 5

SCIENTIFIC INTERACTIONS - SEMINARS AND PAPER PRESENTATIONS

Professional Presentations

Invited Lectures:

Ghia, K.N. and Ghia, U., presented at Science Applications Interaction, Inc., La Jolla, California, July 1989.

Ghia, K.N., Ghia, U. and Osswald, G.A., presented at Science Applications International, Inc., Annapolis, Maryland, June 1989.

Ghia, K.N., presented at The Ohio State University, Columbus, Ohio, February 1989.

Ghia, U., presented at The Ohio State University, Columbus, Ohio, February, 1989.

Ghia, K.N., Ghia, U. and Osswald, G.A., presented at SUBTECH University Program Meeting, Annapolis, Maryland, December 1988.

Osswald, G.A., presented at Air Force Institute of Technology, Wright Patterson Air Force Base, Dayton, Ohio, August 1988.

Osswald, G.A., Ghia, K.N. and Ghia, U., presented at NASA Langley Research Center, Hampton, Virginia, April 1988.

Ghia, K.N., presented at Department of Applied Mathematics, Brown University, Providence, Rhode Island, March 1988.

Ghia, K.N., presented at Department of Mechanical and Aerospace Engineering, Case Western Reserve University, Cleveland, Ohio, January 1988.

Ghia, K.N., presented at Department of Aeronautics and Astronautics, Naval Postgraduate School, Monterey, California, January 1988.

Ghia, K.N. and Ghia, U., presented at Ohsaki Research Institute, Shimizu Corporation, Tokyo, Japan, September 1987.

Ghia, K.N., presented at CSIRO, Division of Energy Technology, Heightt, Australia, September, 1987.

Ghia, U., presented at CSIRO, Division of Energy Technology, Heightt, Australia, September, 1987.

Ghia, K.N., presented at Aero Propulsion Division, Aeronautical Research Laboratories, Department of Defense, Melbourne, Australia, September, 1987.

Ghia, U., presented at Aero Propulsion Division, Aeronautical Research Laboratories, Department of Defense, Melbourne, Australia, September, 1987.

Ghia, K.N. and Ghia, U., presented at International Symposium on Computational Fluid Dynamics, Sydney, Australia, August 1987.

Ghia, K.N., presented Two Lectures in CFD Lecture Series at Indian Institute of Technology, Bombay, India, August 1987.

Ghia, U., presented Two Lectures in CFD Lecture Series at Indian Institute of Technology, Bombay, India, August 1987.

Ghia, K.N. and Ghia, U. presented at DARPA-URI Symposium on Periodic and Aperiodic Phenomenon Behind Circular Cylinders, Newport, RI, July 1987.

Ghia, K.N. presented at Department of Mechanical Engineering and Applied Mechanics, University of Rhode Island, Providence, RI, July 1987.

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Ghia, K.N., Ghia, U. and Osswald, G.A., "Low Reynolds Number Nearly Chaotic Flows Past Airfoils at High Angle of Attack," 3rd International Symposium on Fluid Dynamics and Supercomputers, Nobeyama, Japan, September 1989.

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Rohling, T., Ghia, K.N., Osswald, G.A. and Ghia, U., "Simulation of Chaotic Flow Using Unsteady Navier-Stokes Equations," presented at the 42nd Annual APS Meeting, Palo Alto, California, November 1989.

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Ghia, K.N., Ghia, U., Osswald, G.A., Blodgett, K., Rohling, T. and Zuo, L., "Research Activities in 1988-1989 of the Institute of Computational Mechanics," presented at the 3rd Annual College of Engineering Conference, Cincinnati, Ohio, October 1989.

Ghia, K.N., Osswald, G.A. and Ghia, U., "Chaotic Behavior in High-Incidence Low-Reynolds Number Flows," presented at 3rd Joint ASCE/ASME Mechanics Conference, La Jolla, California, July 1989.

Osswald, G.A., Ghia, K.N. and Ghia, U., "Analysis of Potential and Viscous Flows Past General Two-Dimensional Bodies with Arbitrary Trailing Edge Geometries," presented at AIAA 9th Computational Fluid Dynamics Conference, Buffalo, New York, June 1989.

Ghia, K.N., Osswald, G.A. and Ghia, U., "Study of Low-Reynolds Number Separated Flow Past the Wortmann FX 63-137 Airfoil," presented at Conference on Low Reynolds Number Aerodynamics, Notre Dame, Indiana, June 1989.

*DeChant, L.J. and Ghia, U., "Numerical Simulation of Non-Newtonian Flow of a Modified Bingham Fluid in Channels and Pipes," presented at AIAA 15th Annual Mini-Symposium on Aerospace Science and Technology, Dayton, Ohio, March 1989.

Huang, Y., Ghia, U. and Ghia, K.N., "Unsteady Flow in a Pipe with Temporally Deforming Orifice Plate," presented at AIAA 15th Annual Mini-Symposium on Aerospace Science and Technology, Dayton, Ohio, March 1989.

Osswald, G.A., Ghia, K.N. and Ghia, U., "Unsteady Navier-Stokes Simulation of Incompressible Flow About Arbitrary Two-Dimensional Bodies," presented at AIAA 15th Annual Mini-Symposium on Aerospace Science and Technology, Dayton, Ohio, March 1989.

Thornburg, H.J., Ghia, U. and Ghia, K.N., "Solution-Adaptive Grid Dependent on Gradients and Curvature of Flow Variables," presented at AIAA 15th Annual Mini-Symposium on Aerospace Science and Technology, Dayton, Ohio, March 1989.

Ghia, U., Zuo, L. and Ghia, K.N., "Analysis and Control of Unsteady Separated Flows," presented at AIAA 2nd Shear Flow Control Conference, Tempe, Arizona, March 1989.

Ghia, K.N., Osswald, G.A., Ghia, U. and Blodgett, K., "Analysis of Massively Separated Flow Past Bluff Bodies at High Angles of Attack," presented at the 41st APS Meeting, Buffalo, New York, November 1988.

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Ghia, K.N., Ghia, U., Osswald, G.A., Blodgett, K. and Zuo, L., "Research Activities in 1987-88 of the Institute of Computational Mechanics," presented at the 2nd Annual College of Engineering Conference, Cincinnati, Ohio, October 1988.

Blodgett, K., Ghia, K.N., Osswald, G.A. and Ghia, U., "Unsteady Viscous Flow Past an Elliptic Cylinder," presented at First National Congress in Fluid Dynamics, Cincinnati, Ohio, July 25-28, 1988.

Rice, A., Ghia, K.N., Osswald, G.A., and Ghia, U., "Analysis of Symmetric Wake Behind a Circular Cylinder Using a Direct Solution Technique and Newton's Method," presented at First National Congress in Fluid Dynamics, Cincinnati, Ohio, July 25-28, 1988.

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* Best Paper Award; AIAA Mini-Symposium, 1989.

Zuo, L., Ghia, U., and Ghia, K.N., "Numerical Simulation of Control of Separated Flows," presented at First National Congress in Fluid Dynamics, Cincinnati, Ohio, July 25-28, 1988.

Ramamurti, R., Ghia, U., and Ghia, K.N., "Simulation of Unsteady Flow Past Sharp Shoulders on Semi-Infinite Bodies," presented at 11th International Conference on Numerical Methods in Fluid Dynamics, Williamsburg, Virginia, June 27-July 1, 1988.

Osswald, G.A., Ghia, K.N. and Ghia, U., "Direct Method for Solution of Three-Dimensional Unsteady Incompressible Navier-Stokes Equations," presented at 11th International Conference on Numerical Methods in Fluid Dynamics, Williamsburg, Virginia, June 27-July 1, 1988.

*Osswald, G.A., Ghia, K.N. and Ghia, U., "Post-Simulation Analysis of Unsteady Attractor Solutions for the Unsteady Navier-Stokes Equations," AIAA 14th Annual Mini-Symposium on Aerospace Science and Technology, Dayton, Ohio, March 31, 1988.

Blodgett, K., Ghia, K.N., Osswald, G.A. and Ghia, U., "Unsteady Viscous Flow Past an Elliptic Cylinder," AIAA 14th Annual Mini-Symposium on Aerospace Science and Technology, Dayton, Ohio, March 31, 1988.

Satyanarayana, P., Ghia, U. and Ghia, K.N., "Analysis of Flow Through a Pipe-Orifice, Including Orifice-Plate Deformation," AIAA 14th Annual Mini-Symposium on Aerospace Science and Technology, Dayton, Ohio, March 31, 1988.

Ramamurti, R., Ghia, U. and Ghia, K.N., "Navier-Stokes Analysis of Separated Flow Past Thick Semi-Infinite Bodies," AIAA 14th Annual Mini-Symposium on Aerospace Science and Technology, Dayton, Ohio, March 31, 1988.

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Ghia, K.N. and Slater, G., "Research Activities of the Institute for Computational Mechanics," presented at The First Annual Conference of College of Engineering on Technological Innovation for Economic Growth, Cincinnati, Ohio, October, 1987.

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Ghia, U., Ramamurti, R. and Ghia, K.N., "Study of Viscous Flows with Upstream Interaction Using Interacting PNS Equations," presented at the R.T. Davis Symposium on Computational Mechanics, Cincinnati, Ohio, June 1987.

Ghia, K.N., Liu, C.A., Ghia, U. and Osswald, G.A., "Analysis of Unsteady Wake of a Circular Cylinder Using Navier-Stokes Equations," presented at ASME Forum on Unsteady Flow Separation, Cincinnati, Ohio, June 1987.

Osswald, G.A., Ghia, K.N., and Ghia, U., "A Direct Algorithm for Solution of Incompressible Three-Dimensional Unsteady Navier-Stokes Equations," AIAA 87-1139-CP, presented at AIAA 8th Computational Fluid Dynamics Conference, Honolulu, Hawaii, June 1987.

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* Best Paper Award, AIAA Mini-Symposium, 1988.

Collopy, G., Ghia, K.N., Ghia, U. and Osswald, G.A., "Determination of Discharge Coefficients for a Pipe-Orifice Using the Navier-Stokes Equations," presented at AIAA 13th Annual Minisymposium on Aerospace Science and Technology, Dayton, Ohio. March 1987.

Zuo, L., Ghia, U. and Ghia, K.N., "Efficient Numerical Grid Generation Methods Based on Conformal Mapping," presented at AIAA 13th Annual Minisymposium on Aerospace Science and Technology, Dayton, Ohio, March 1987.

Rocker, M. and Ghia, K.N., "Analysis of High Incidence Aerodynamic Flow Past Arbitrary Lifting Airfoils Using Unsteady Navier-Stokes Equations," presented at AIAA 13th Annual Minisymposium on Aerospace Science and Technology, Dayton, Ohio, March 1987.

Ghia, K.N., Ghia, U., Liu, C.A. and Osswald, G.A., "Study of Unsteady Wake Behind a Circular Cylinder Using Time-Dependent Simulation," Bull. Am. Phys. Soc., Vol. 31, No. 10, 1986, pp. 1746; presented at the 39th APS Meeting, Columbus, Ohio, November, 1986.

SECTION 6

STUDENT DEGREE THESES AND DISSERTATIONS

M.S. DEGREE THESES

Collopy, G.B., "Determination of Flow, Including Discharge Coefficients, In a Pipe-Orifice Using Unsteady, Navier-Stokes Equations," M.S. Thesis, Department of Aerospace Engineering and Engineering Mechanics, University of Cincinnati, Cincinnati, Ohio, June 1987.

Liu, C.A., "Study of a Two-Dimensional Viscous Flow Past a Circular Cylinder Using Unsteady Navier-Stokes Equations," M.S. Thesis, Department of Aerospace Engineering and Engineering Mechanics, University of Cincinnati, Cincinnati, Ohio, June 1987.

Rocker, M., "Analysis and Development of Conformal Grid Generation Technique for Flow Past Arbitrary Airfoils at High Incidence," M.S. Thesis, Department of Aerospace Engineering and Engineering Mechanics, University of Cincinnati, Cincinnati, Ohio, June 1987.

Zuo, L., "Efficient Numerical Grid-Generation Methods Based on Conformal Mapping," M.S. Thesis, Department of Aerospace Engineering and Engineering Mechanics, University of Cincinnati, Cincinnati, Ohio, December 1987.

De Chant, L.J., "Analysis and Numerical Simulation of Modified Bingham (Non-Newtonian) Fluid Flow in Channels and Pipes," M.S. Thesis, Department of Mechanical and Industrial Engineering, University of Cincinnati, Cincinnati, Ohio, June 1989.

Rice, A.B., "Simulation of Symmetric Wake of a Cylinder with Unsteady Navier-Stokes Analysis: Application of Newton's Acceleration Technique to a Direct Numerical Method," M.S. thesis, Department of Aerospace Engineering and Engineering Mechanics, University of Cincinnati, Cincinnati, Ohio, June 1989.

PH.D. DEGREE DISSERTATIONS

Liao, C.W., "Analysis and Numerical Solutions of Flow over Airfoil with Control Flap," Ph.D. Dissertation, Department of Mechanical and Industrial Engineering, University of Cincinnati, Cincinnati, Ohio, March 1989.

Sofronis, I., "Analysis of Viscous Flow in Turbomachinery," Ph.D. Dissertation, Department of Mechanical and Industrial Engineering, University of Cincinnati, Cincinnati, Ohio, December 1987.

Ramamurti, R., "A Semi-Elliptic Analysis and Hybrid C-H Grids for Two-Dimensional Viscous Flows Through Cascades," Ph.D. Dissertation, Department of Mechanical and Industrial Engineering, University of Cincinnati, Cincinnati, Ohio, June 1986.

SECTION 7

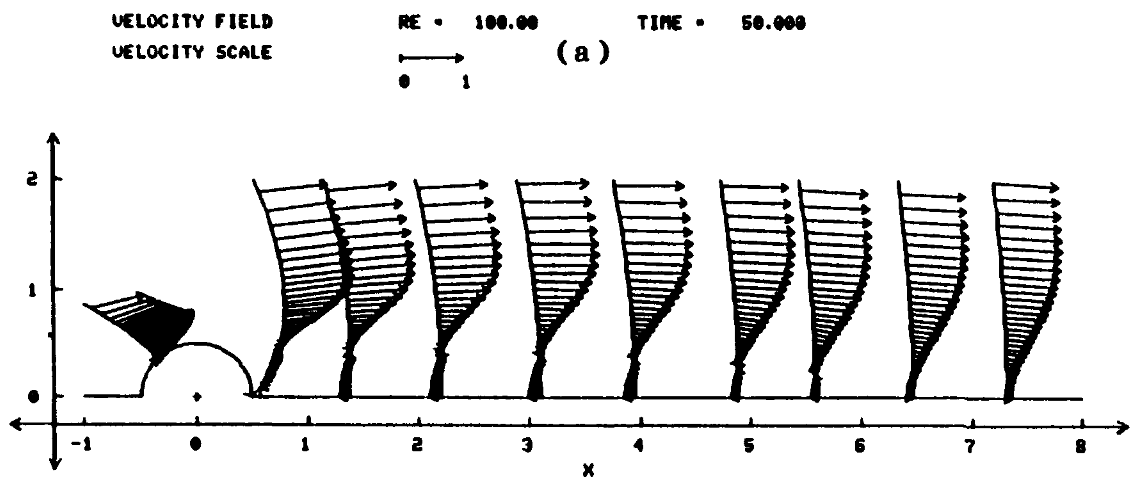
TECHNICAL APPLICATIONS

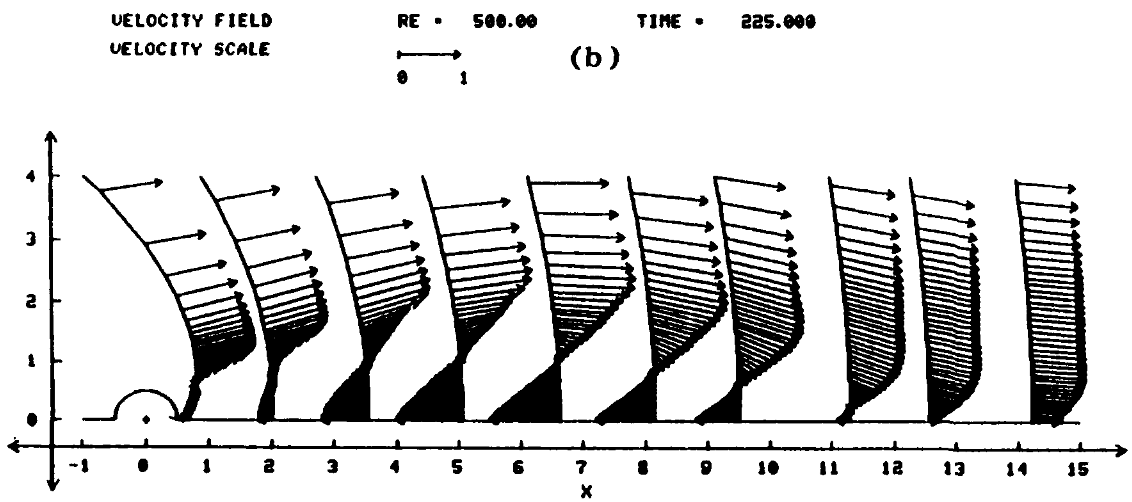
Of the various CFD analyses developed, some were of direct use to the technical community. Although to our knowledge, none of these analyses were used in the development of any specific hardware, they are being used in preliminary design studies by analysts in the industry. Some of these analyses are also being used by other researchers at governmental laboratories to improve their analyses. The following is a list of the CFD analyses and the organizations using them.

ANALYSIS	ORGANIZATION
⊙ Two-Dimensional Unsteady Navier-Stokes Analysis for Bluff Body Separation	University of Houston, Houston, TX.
⊙ Multigrid-Strongly Implicit Analysis for Unsteady Navier-Stokes Equations	Naval Post Graduate School, Monterey, CA.
⊙ Axisymmetric Unsteady Navier-Stokes Analysis for Internal Flows	The Ohio Supercomputer Center, Columbus, OH.
⊙ Two-Dimensional Unsteady Navier-Stokes Analysis for High Angle of Attack Aerodynamics	NASA Langley Research Center, Hampton, VA.
⊙ Three-Dimensional Unsteady Navier-Stokes Analysis	Science Applications International Inc., Annapolis, MD.

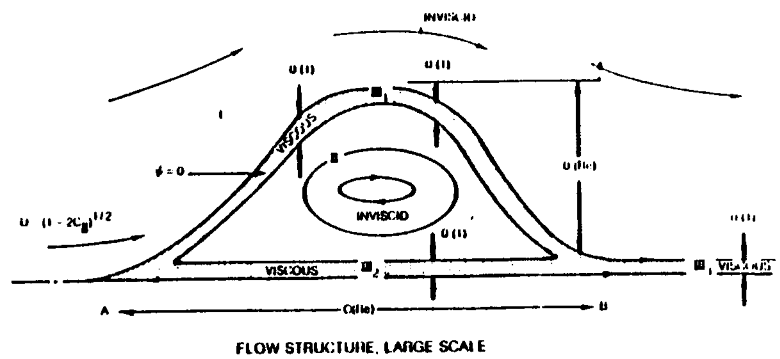
TABLE I. AIRFOIL FLOW CONFIGURATIONS INVESTIGATED: Re = 1000.

Case	Airfoil Geometry; TE Geometry	Configuration No. $\alpha=5°$	$\alpha=15°$	Comments
I	12% Symmetric Joukowski	1	2	Flow results included
II	NACA 0012; with Wedge TE	3	4	Flow results included
III	NACA 0012; with Rounded TE	5	6	Flow results included
IV	NACA 0012; with Bluff TE	7	8	Flow results not included

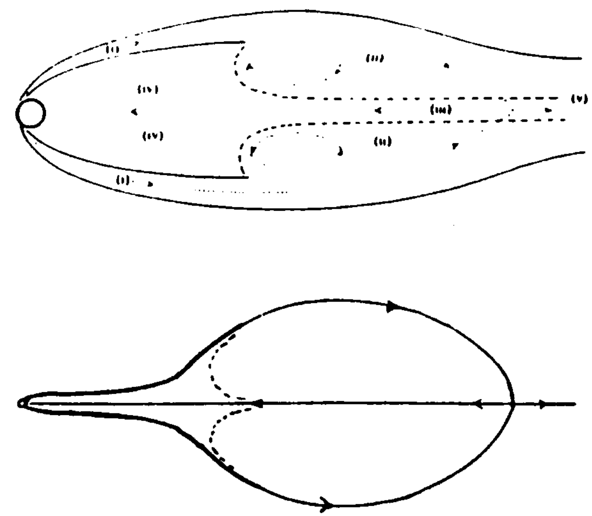




PRESENT CALCULATIONS

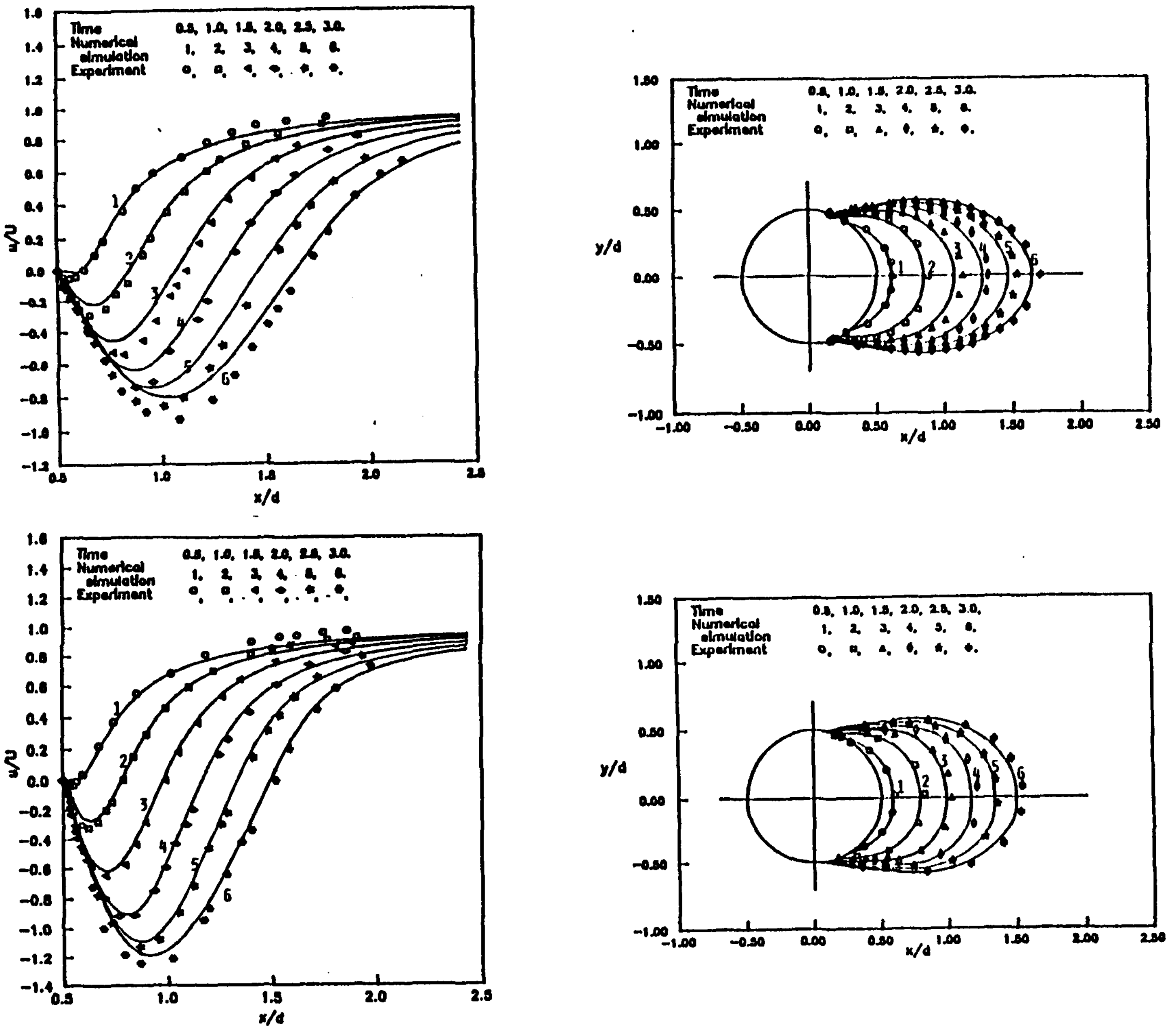


ASYMPTOTIC MODEL (SMITH [1986])



ASYMPTOTIC MODELS
(PEREGRINE [1985])

FIG. 1. LARGE-SCALE CHARACTERESTICS FOR FLOW PAST CYLINDER



VELOCITY ALONG WAKE-CENTERLINE

WAKE BOUNDARY

FIG. 2. EARLY-TIME FLOW CHARACTERISTICS FOR CYLINDER
(a),(b) : Re = 200 : (c),(d) : Re = 550.
SYMBOLS: EXPERIMENTS OF BOUARD & COUTANCEAU ______ PRESENT CALCULATIONS

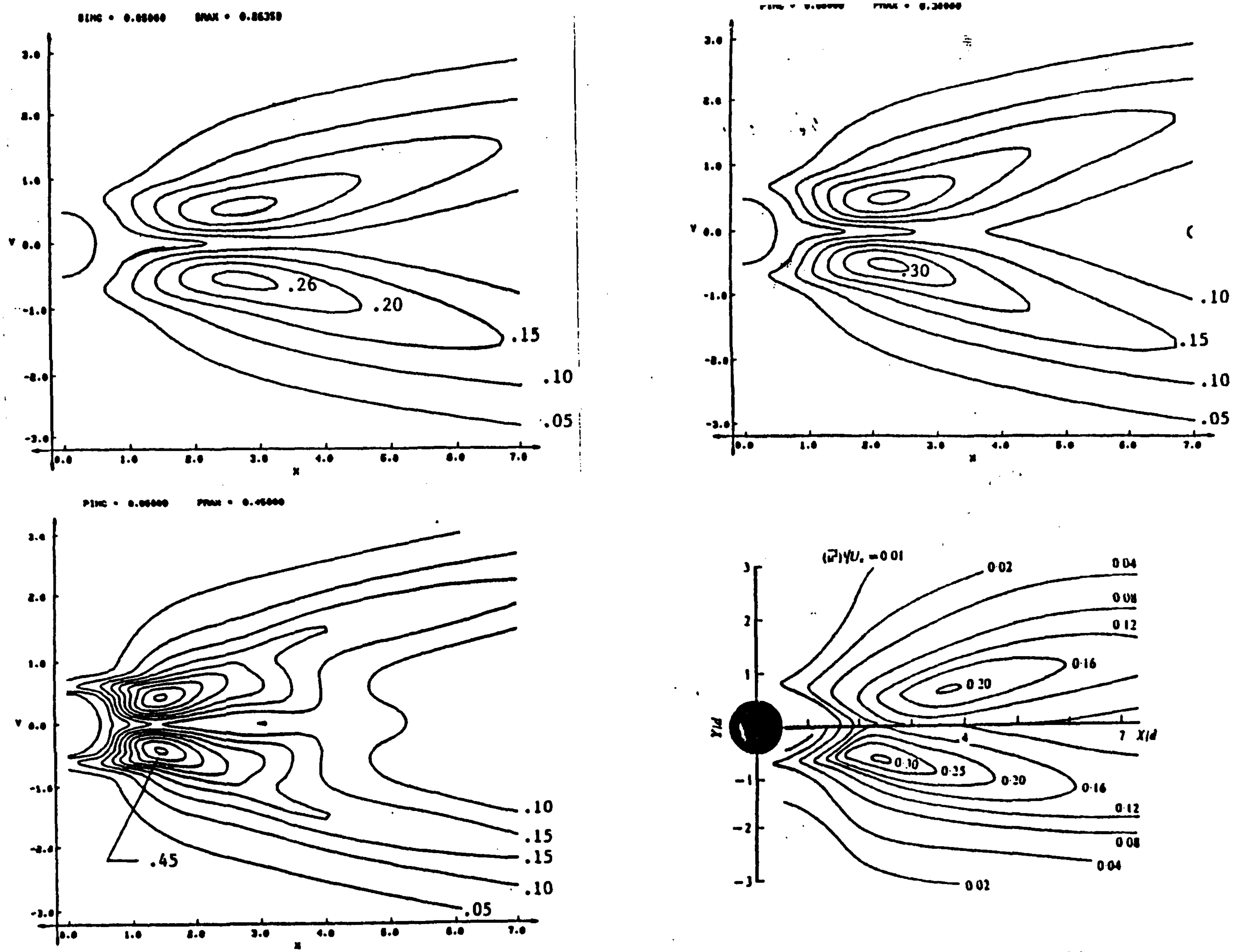
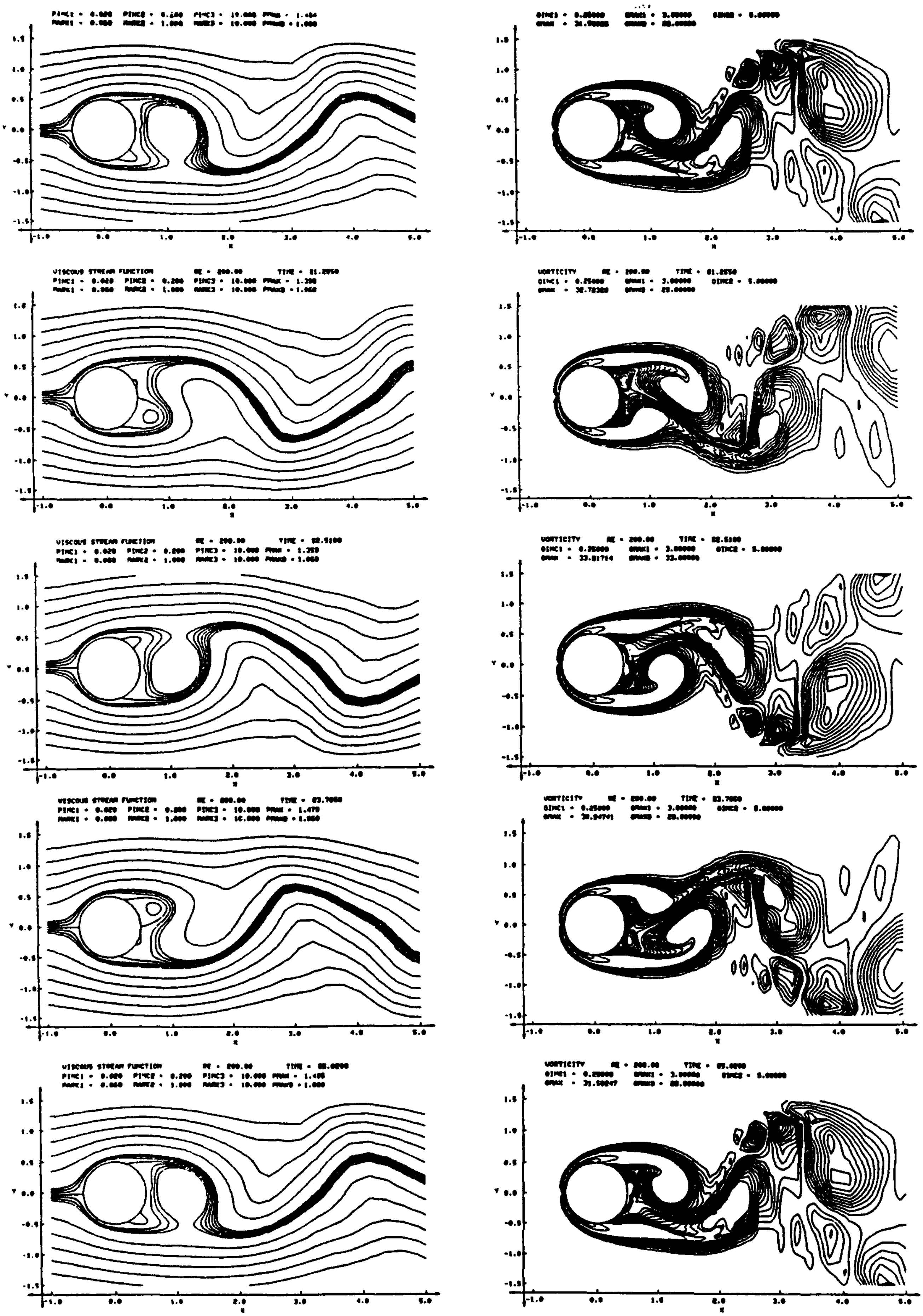
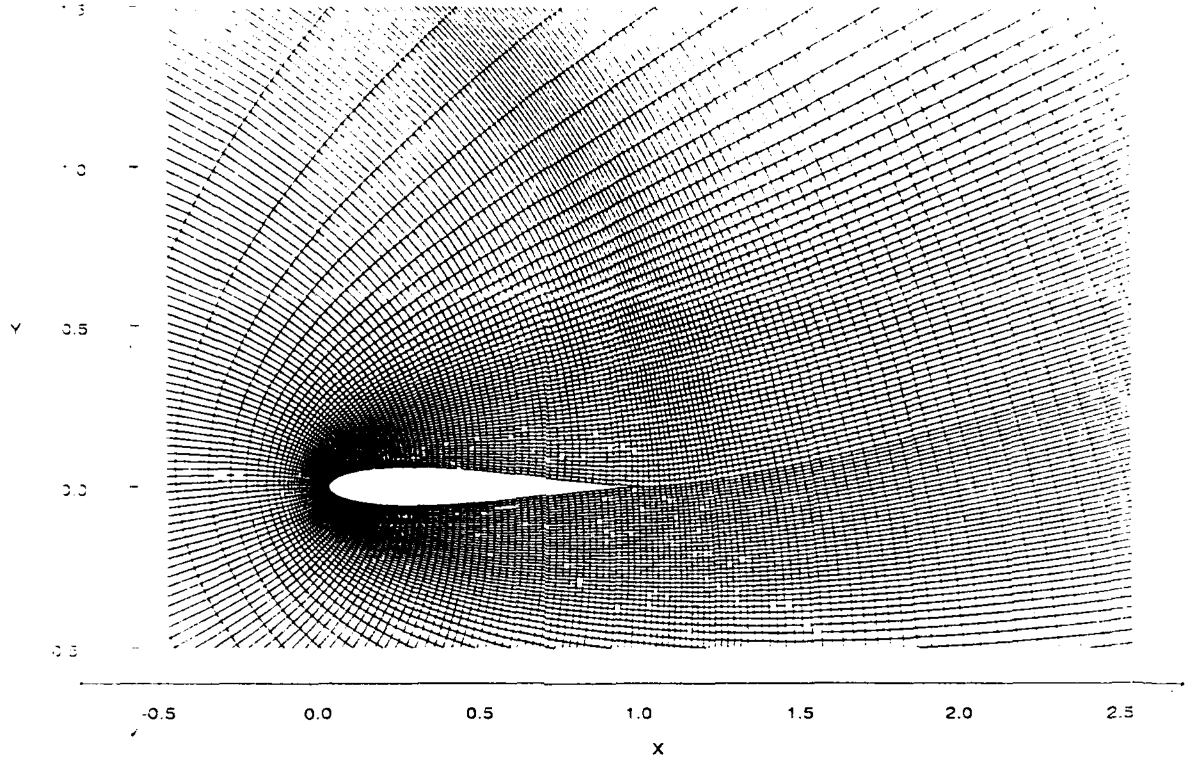


FIG. 3. NORMALIZED REYNOLDS STRESS $\overline{u'u'}^{\frac{1}{2}}$ CONTOURS. A) Re = 80, b) Re = 100, c) Re = 200, d) RESULTS OF NISHIOKA & SATO FOR Re = 70 AND 120.

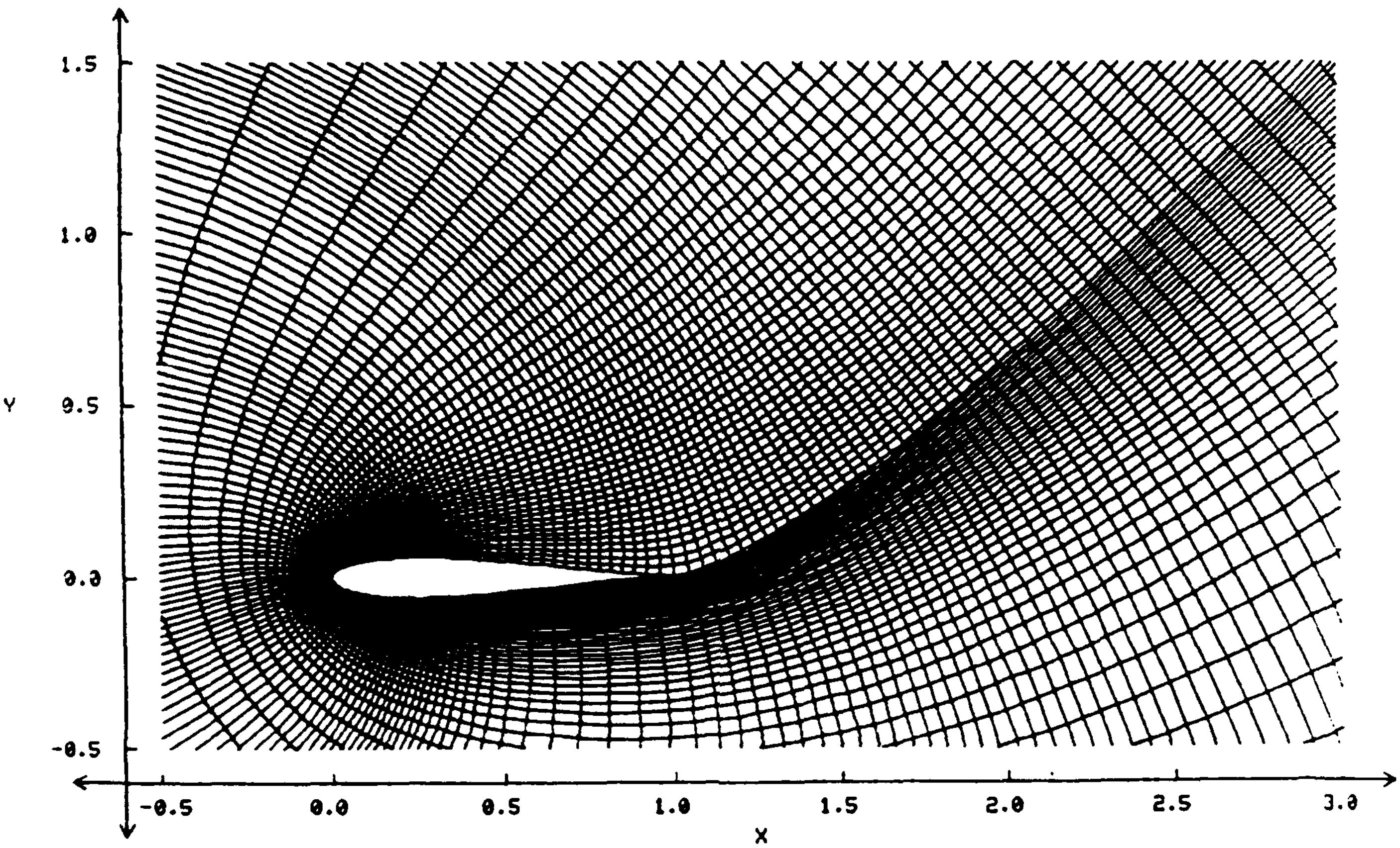


Instantaneous Streamfunction Contours **Instantaneous Vorticy Contours**

FIG. 4. EXAMINATION OF LIMIT CYCLE FOR A CIRCULAR CYLINDER AT Re = 200.

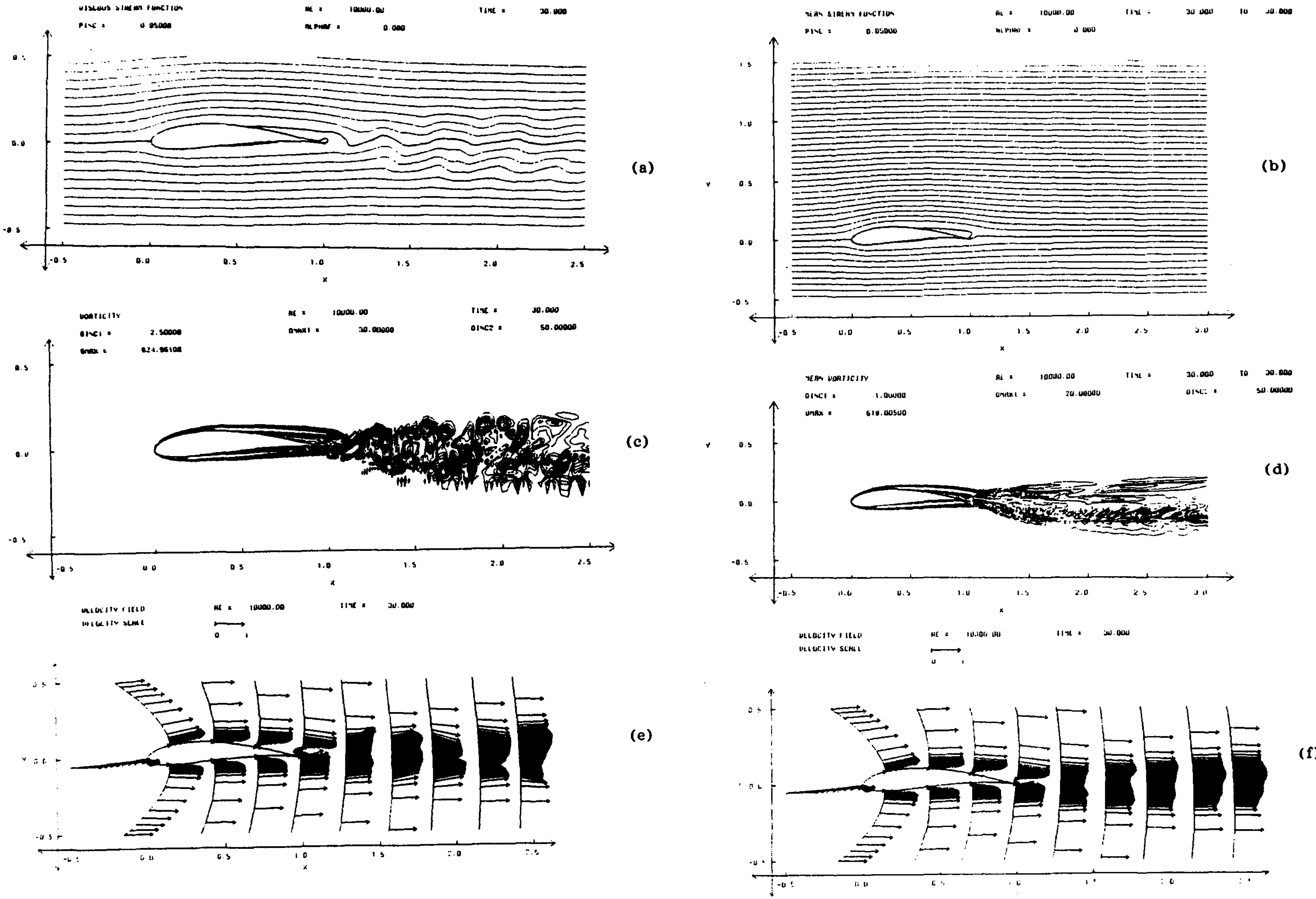


SYMMETRIC JOUKOWSKI AIRFOIL, α = 22° (361x61) POINTS



SYMMETRIC JOUKOWSKI AIRFOIL, α = 53°, (229x46) POINTS

FIG. 5. TYPICAL GRID DISTRIBUTIONS (229x46)



INSTANTANEOUS RESULTS

AVERAGE RESULTS

FIG. **6.** FLOW PAST THE WORTMANN FX 63-137 AIRFOIL AT Re = 10,000, $\alpha_f = 0°$. a) - b) STREAM FUNCTION CONTOURS, c) - d) VORTICITY CONTOURS, e) - f) VELOCITY VECTORS.

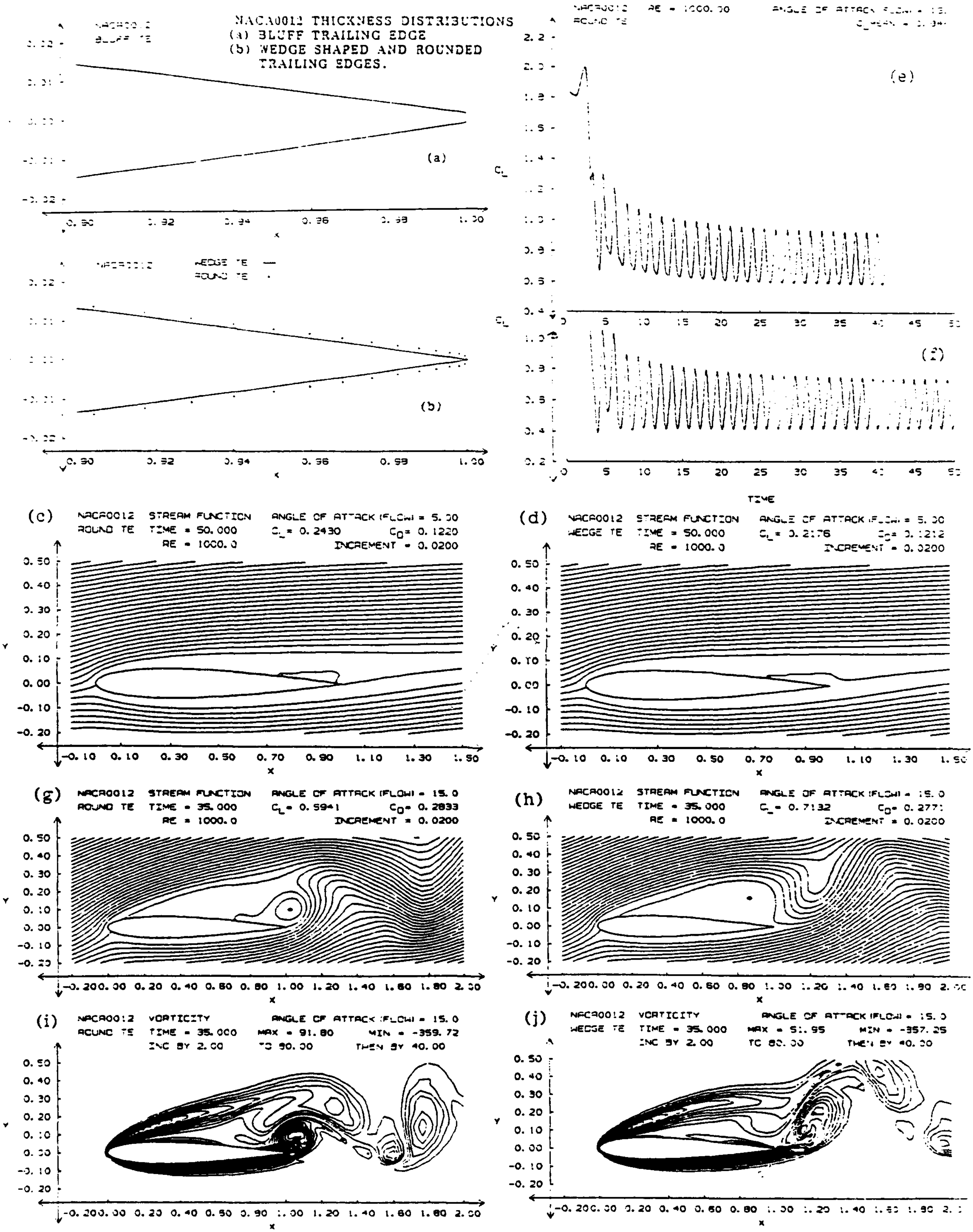


FIGURE 7 RESULTS FOR NACA0012 AIRFOIL.

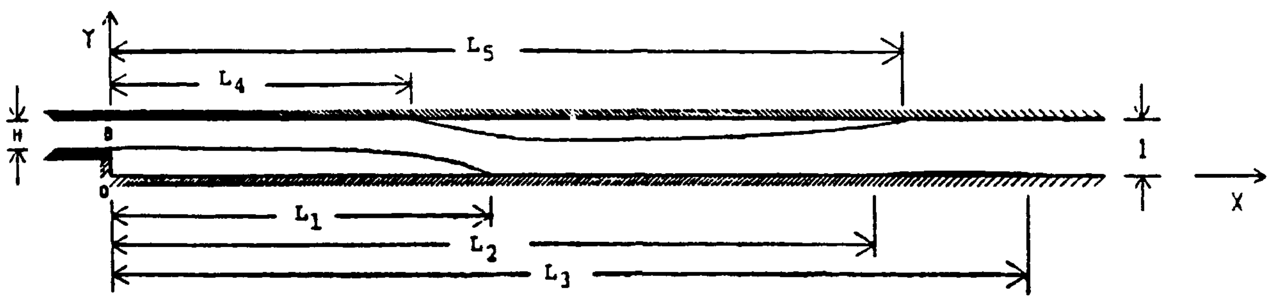


FIG. 8, BACKSTEP CHANNEL GEOMETRY, WITH NOMENCLATURE FOR VARIOUS SEPERATION AND REATTACHMENT LENGTHS.

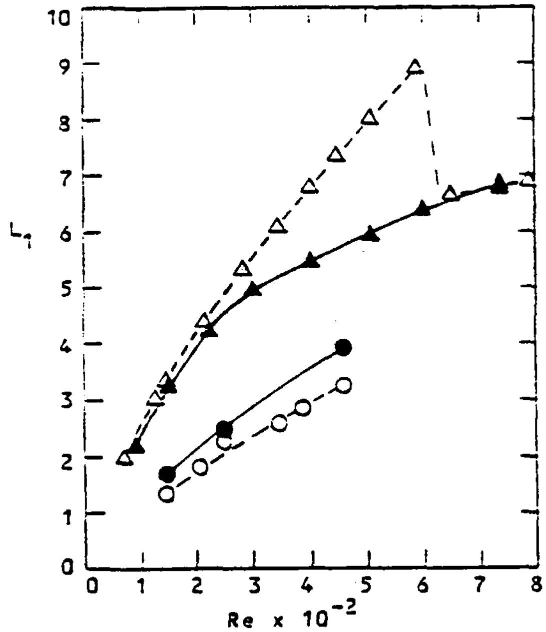


FIG. 9a. SIMILARITY STUDY OF PRIMARY REATTACHMENT LENGTH.

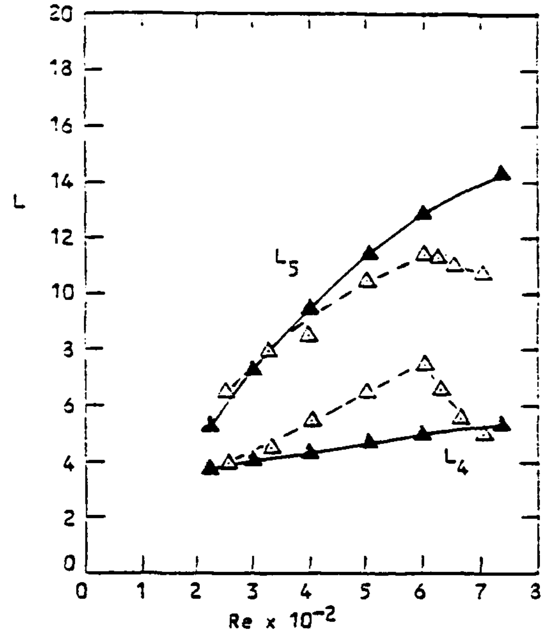


FIG. 9b. SECONDARY SEPARATION AND REATTACHMENT LENGTHS.

CONFIG. \ REF.	PRESENT	ARMALY, DURST (1980)	DENHAM, PATRICK (1974)
H = 0.51485	—▲—	--△--	
H = 0.66667	—●—		--○--
H = 0.90000	—■—		

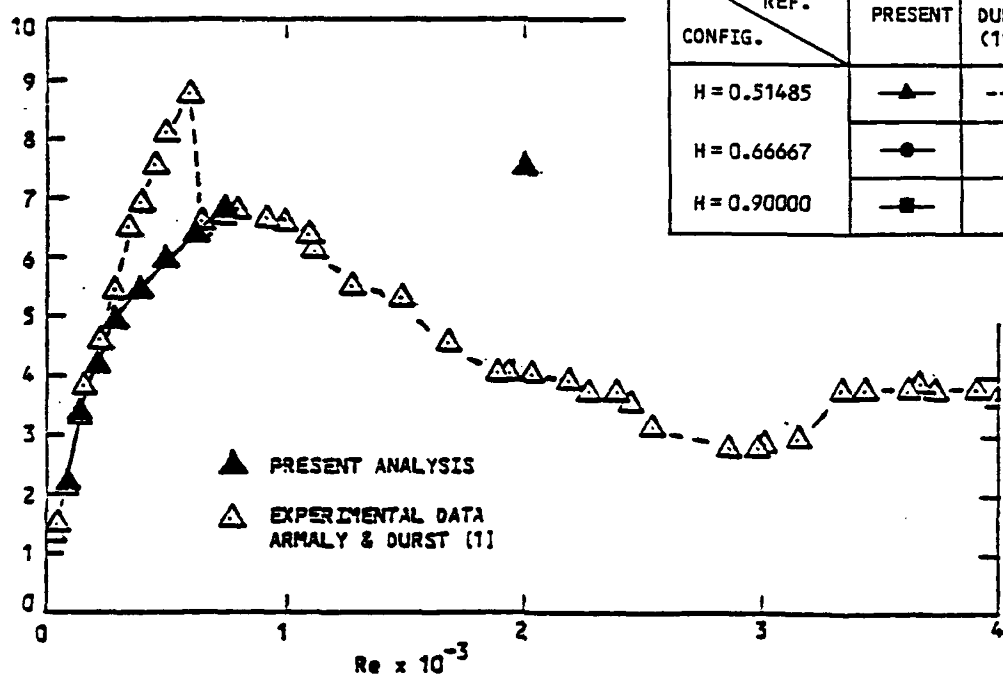


FIG. 9c. COMPARISON OF PRIMARY REATTACHMENT LENGTH IN TRANSITION REGIME.

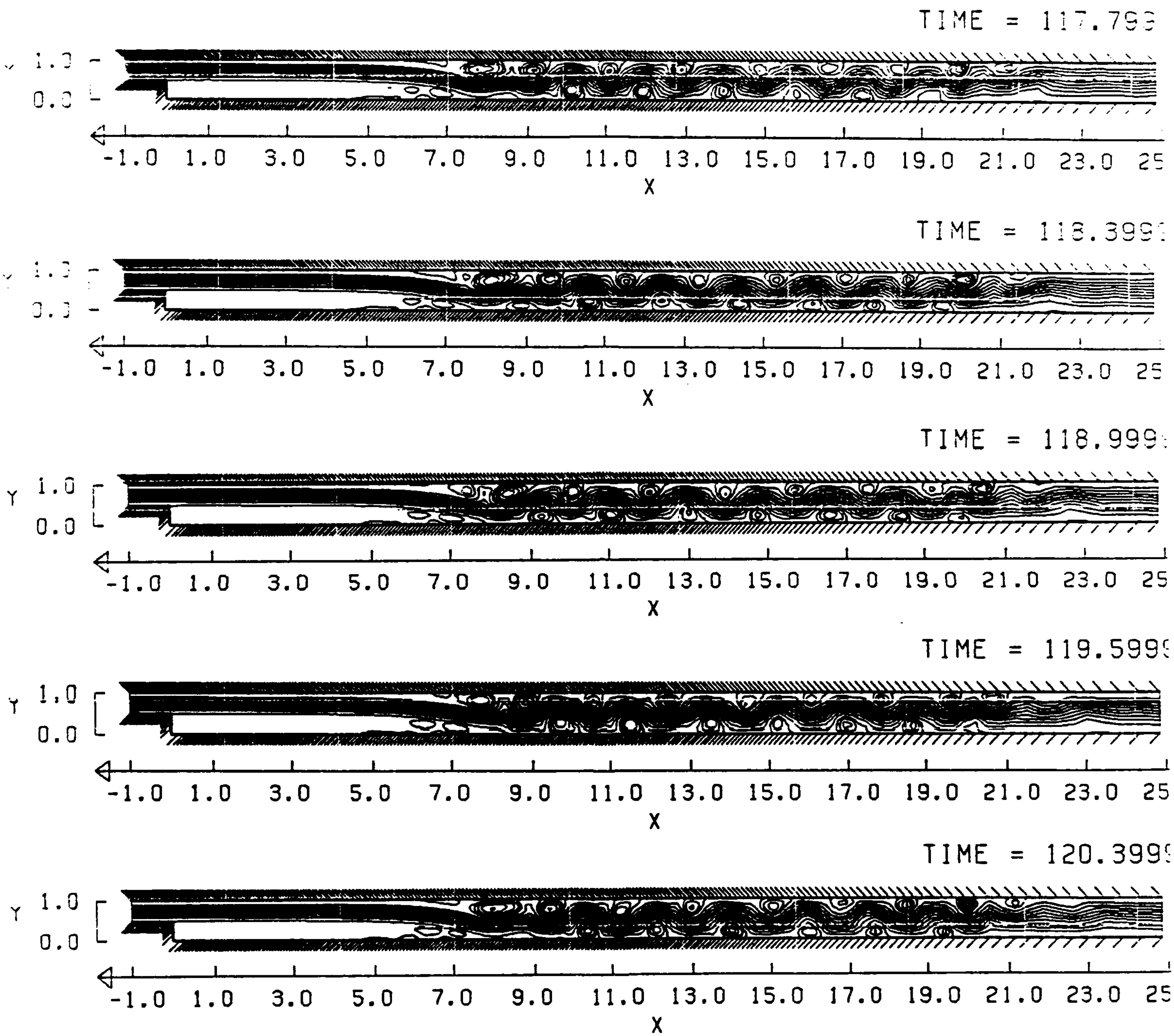


FIG. 10. STREAM-FUNCTION CONTOURS FOR UNSTEADY FLOW IN TRANSITION REGIME; Re = 2000, $\Delta\psi$ = 0.1 FOR MAIN FLOW; $\Delta\psi$ = 0.0536 IN BUBBLES.

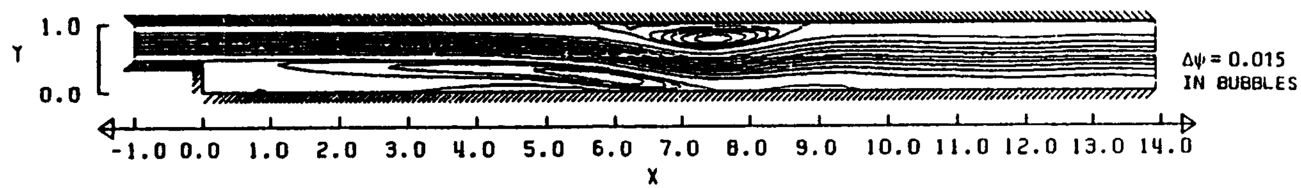


FIG. 11a. TIME-AVERAGED STREAM-FUNCTION CONTOURS FOR $95.02 \leq T \leq 117.00$;
$Re = 2000$, $\Delta\psi = 0.1$.

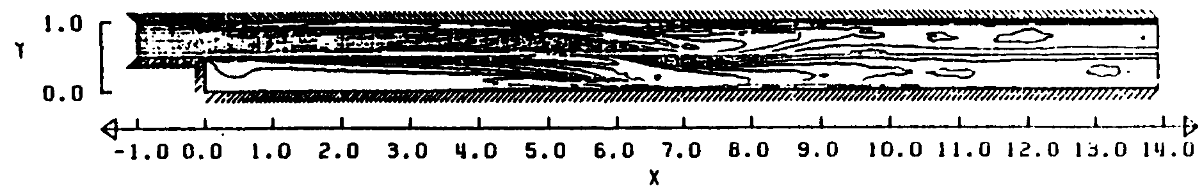
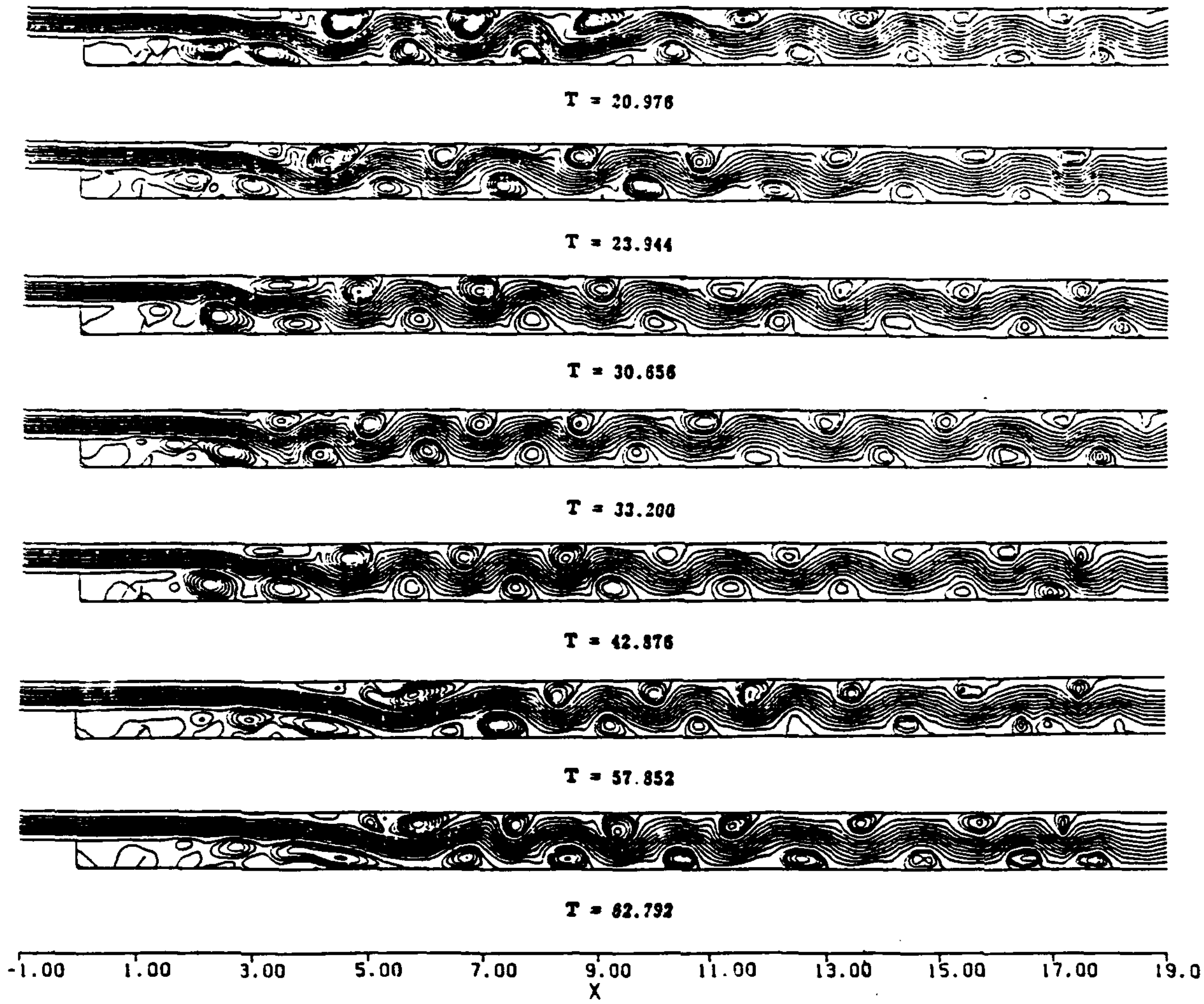


FIG. 11b. TIME-AVERAGED VORTICITY CONTOURS FOR $95.02 \leq T \leq 117.00$;
$Re = 2000$, $\Delta\omega = 2.0$.



Streamfunction Contours

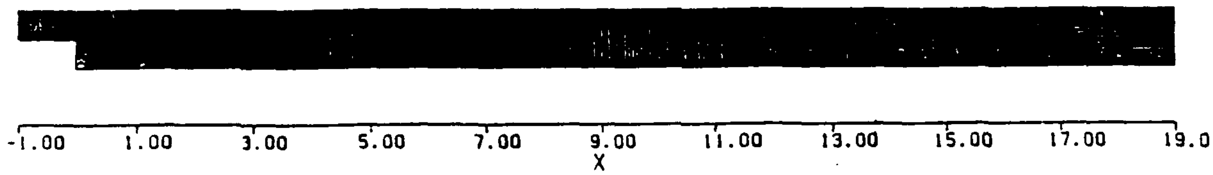
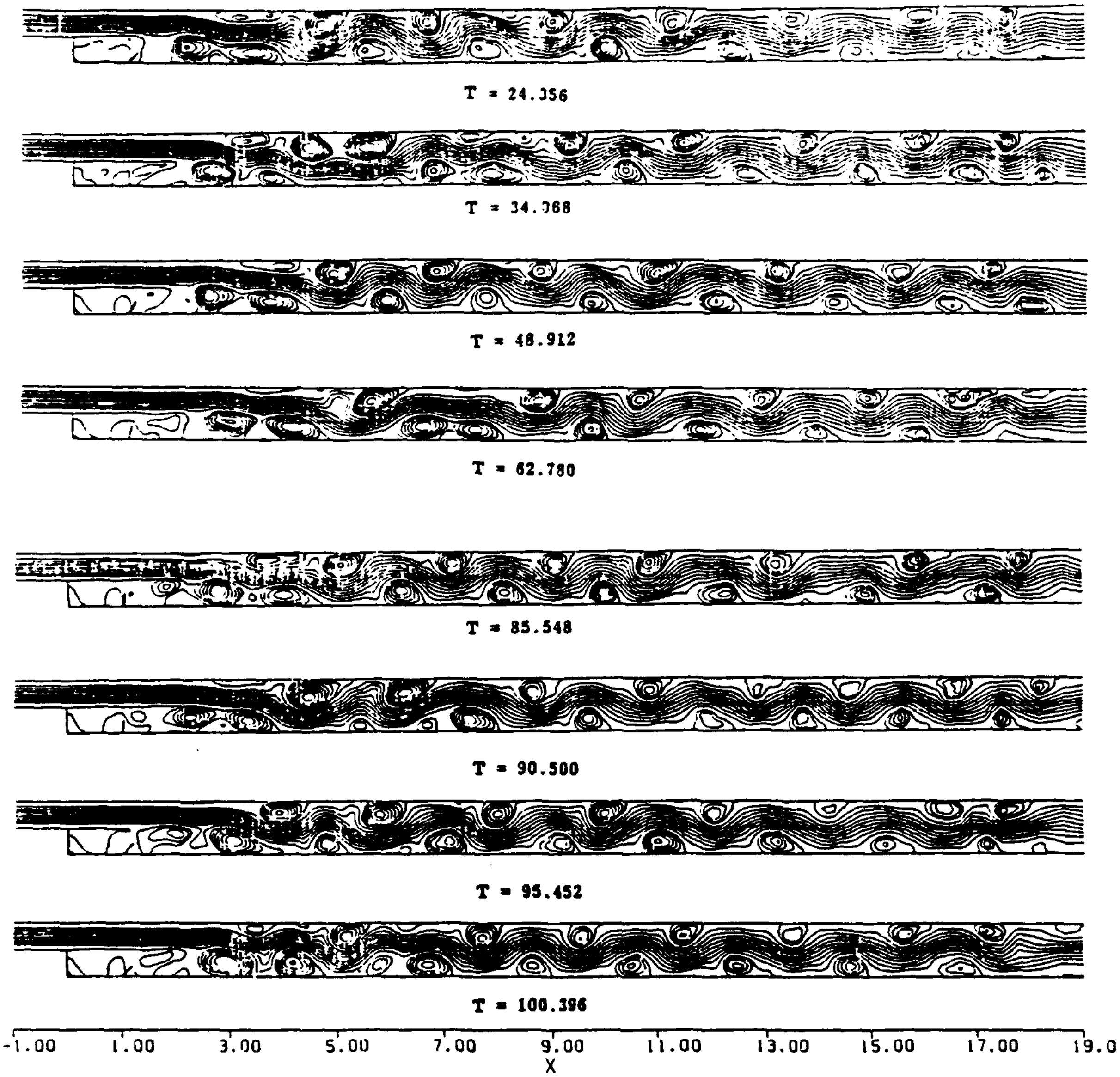


Fig. 12. **Unsteady Flow in Back-Step Channel with an Oscillating Flap**

Re = 2000, F = .16, 45° < θ < 90°, (375,34)

Reduction in Primary Reattachment Length; ≅ 15%.



Streamfunction Contours

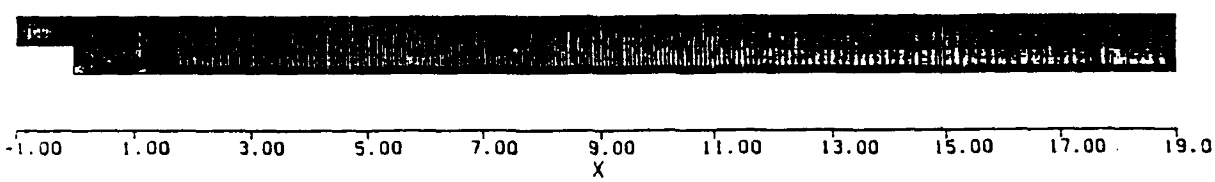


Fig. 13. **Unsteady Flow in Back-Step Channel with an Oscillating Flap**

Re = 2000, F = .25, 45° < θ < 90°, (375,34)

Reduction in Primary Reattachment Length: ≅ 25%.

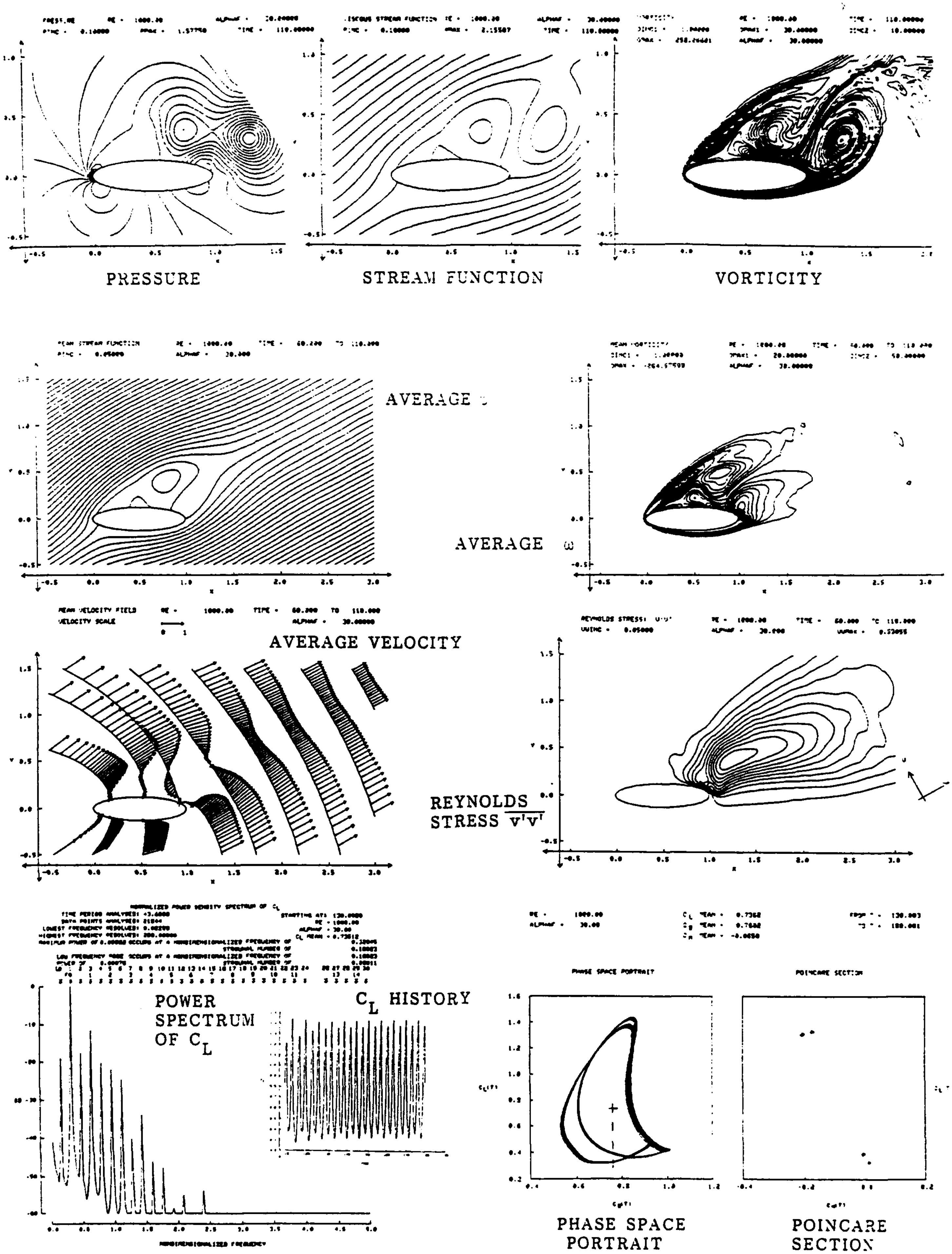


FIG. 14. FLOW PAST A 25% THICK ELLIPSE, Re = 1000, α_f = 30°.

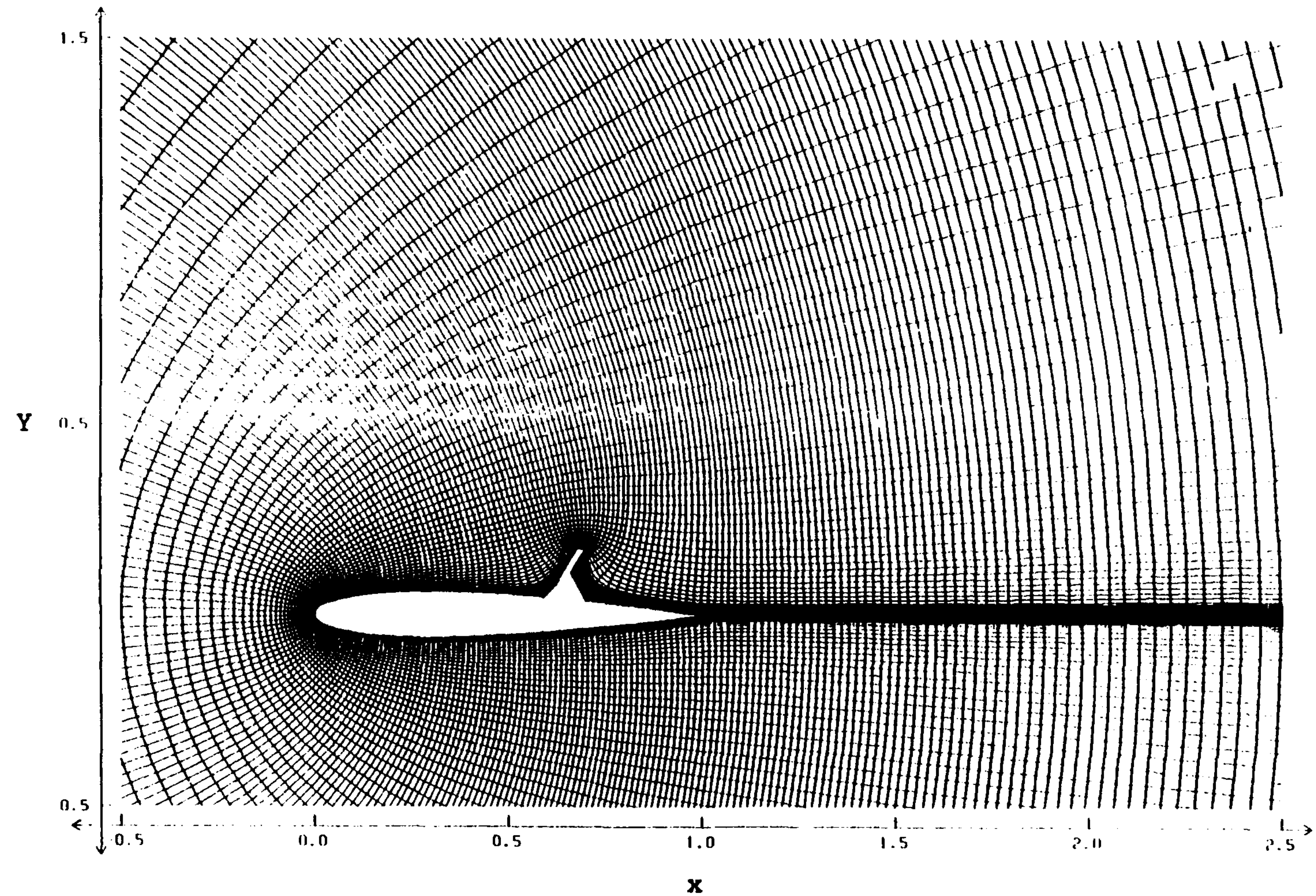


FIG. 15: C-GRID FOR AIRFOIL WITH CONTROL FLAP AT 60% CHORD.

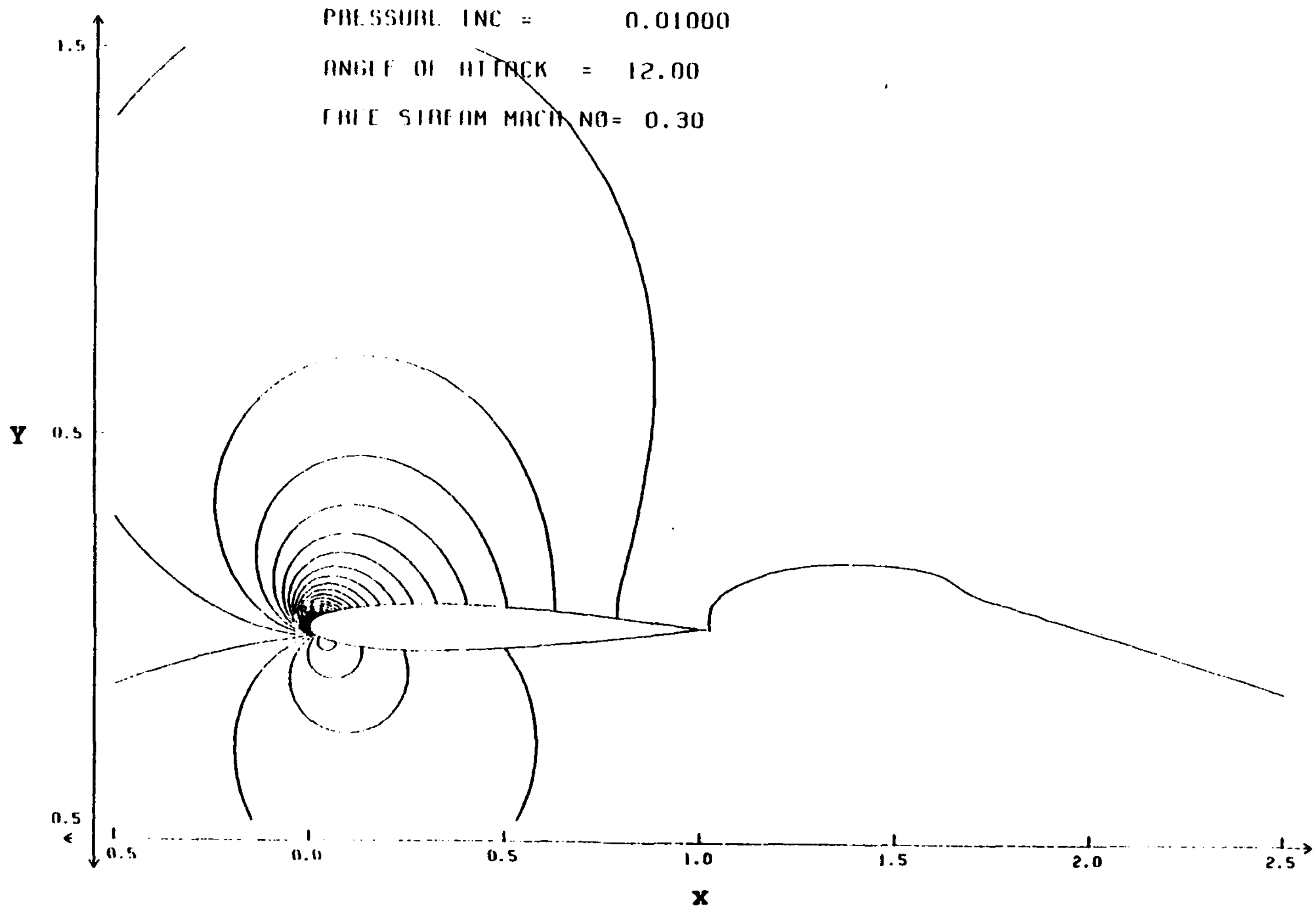


FIG. 16. PRESSURE CONTOURS FOR NACA0012 AIRFOIL
(α_a = 12°, M_∞ = 0.3, Re = $6x10^6$)

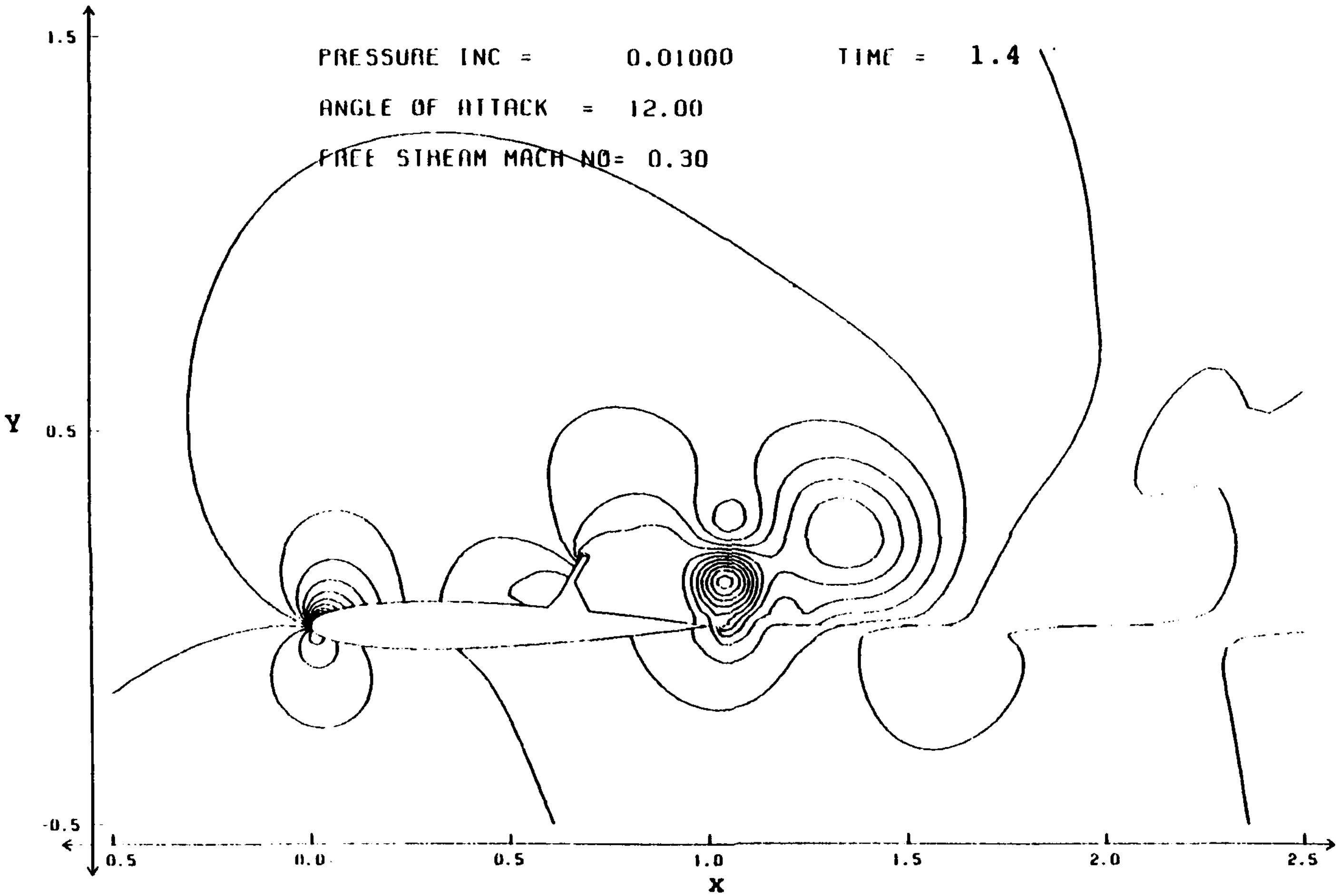


FIG. 17. PRESSURE CONTOURS FOR AIRFOIL WITH CONTROL FLAP AT 60% CHORD (α_a = 12°, Time = 1.4)

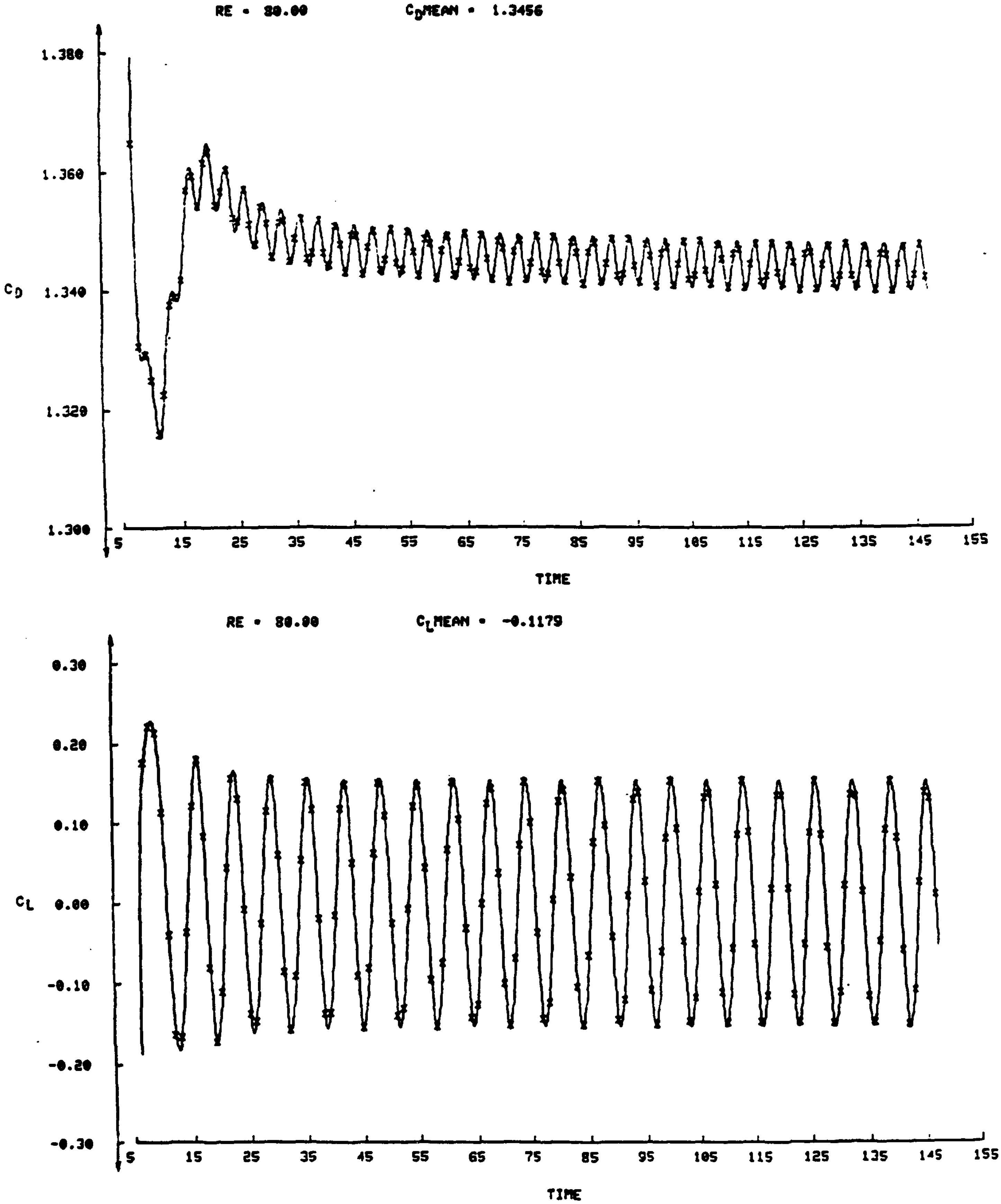
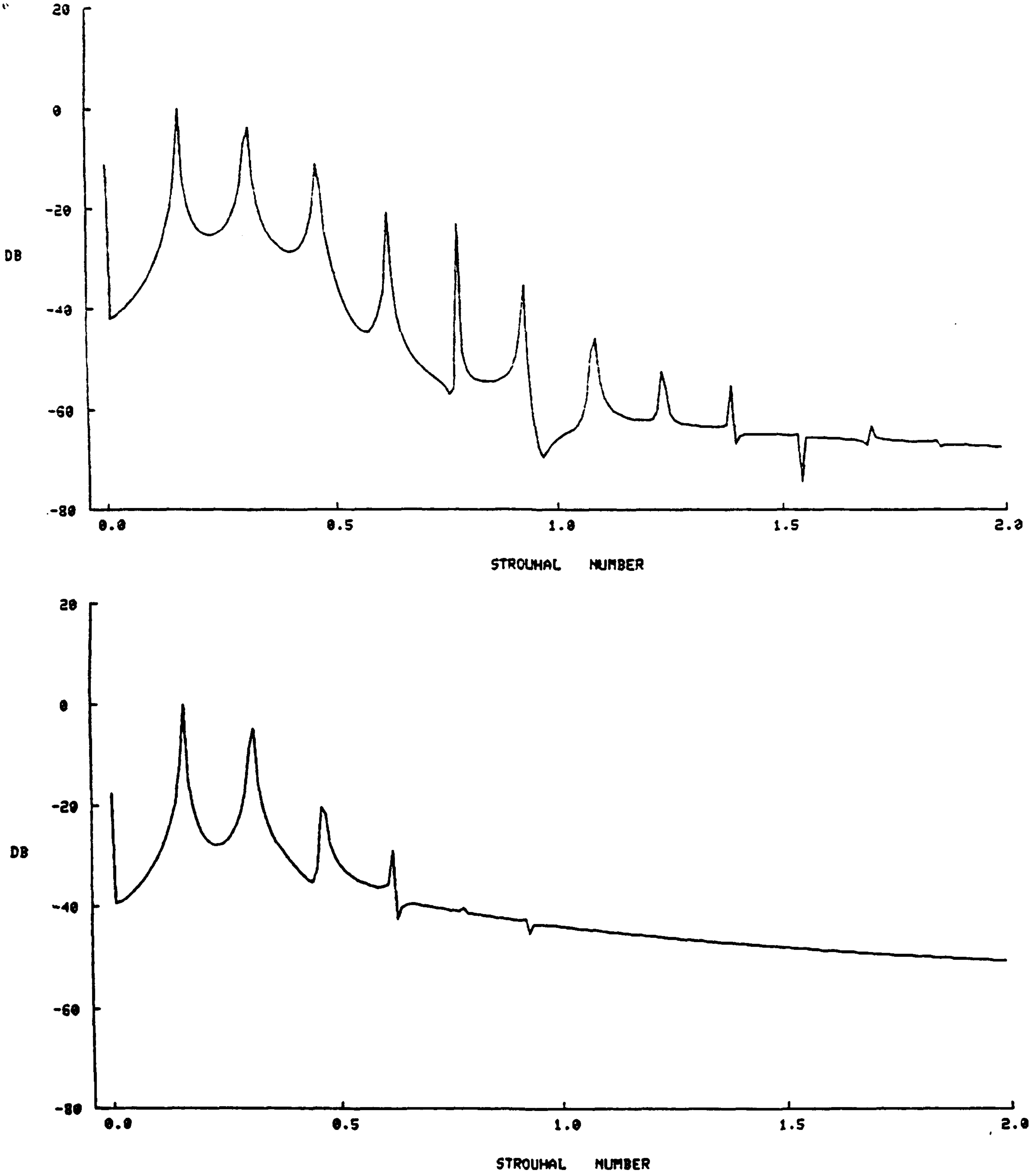


FIG. 18. DRAG AND LIFT HISTORIES FOR CIRCULAR CYLINDER AT RE = 80.



'IG. 19. POWER SPECTRAL DENSITY FOR Re = 80 ; LOCATION (a) (5,1), (b) (10,1).

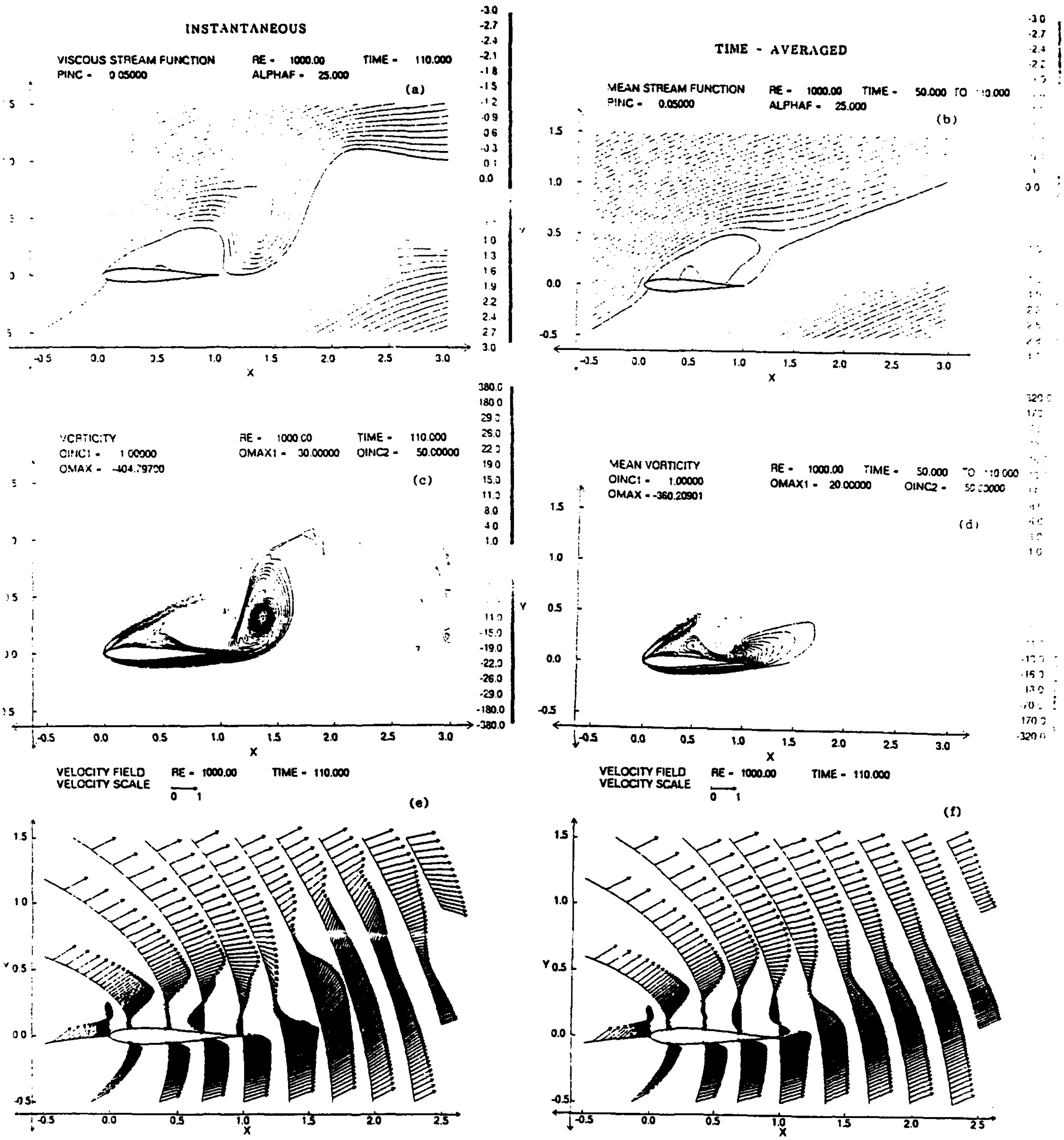


FIG. 20. FLOW PAST A 12% THICK SYMMETRIC JOUKOWSKI AIRFOIL, Re = 1000, $_f$ = 25°, (319,61) GRID.
(a)-(b) STREAM FUNCTION CONTOURS, (c)-(d) VORTICITY CONTOURS, (e)-(f) VELOCITY VECTORS.

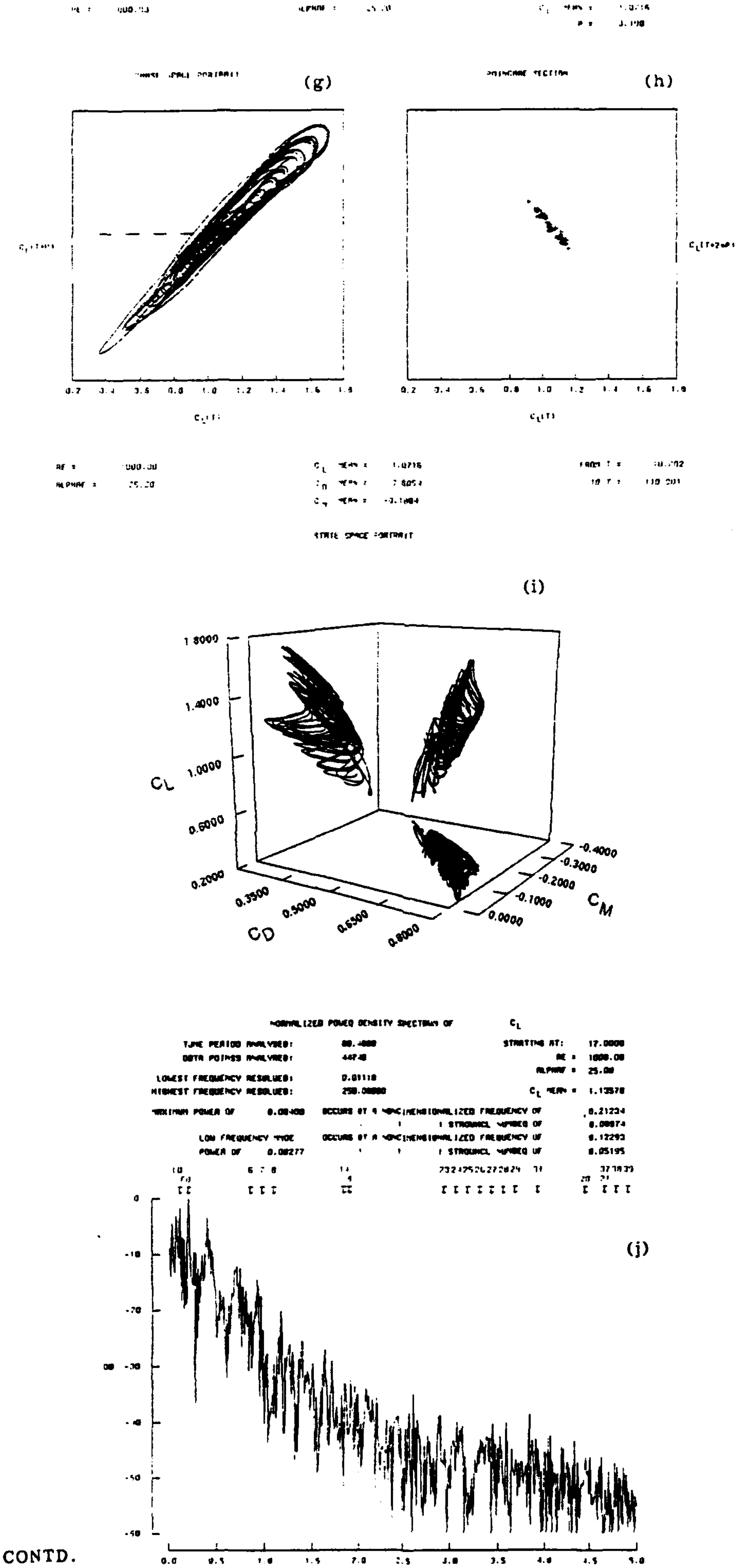


FIG. 20 CONTD.
ANALYSIS OF FLOW PAST A 12% THICK SYMMETRIC JOUKOWSKI AIRFOIL, Re = 1000, $\alpha_f = 25°$,
(g) PHASE SPACE PORTRAIT, (h) POINCARE SECTION, (i) ATTRACTOR, (j) POWER SPECTRUM OF C_L.